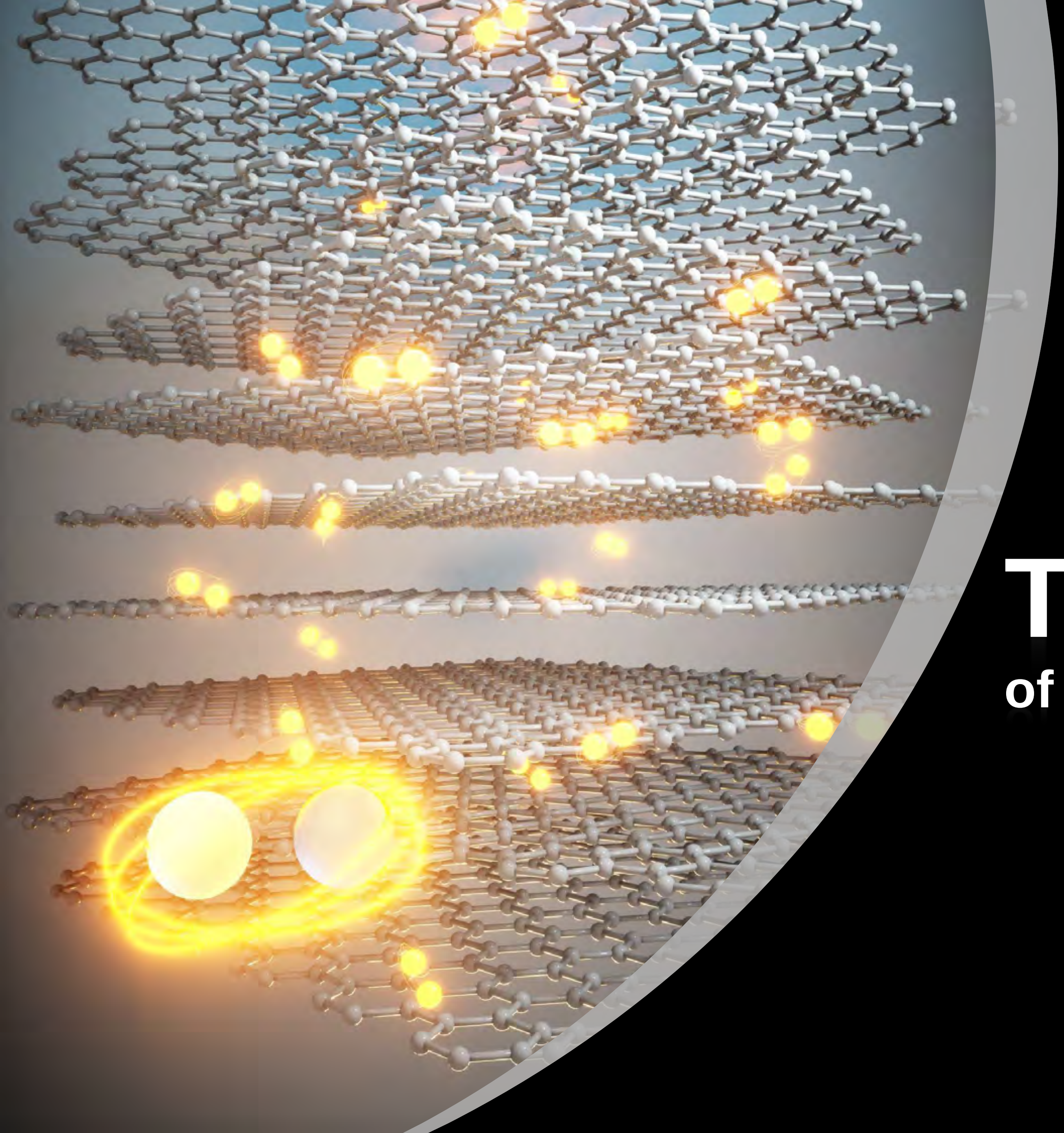


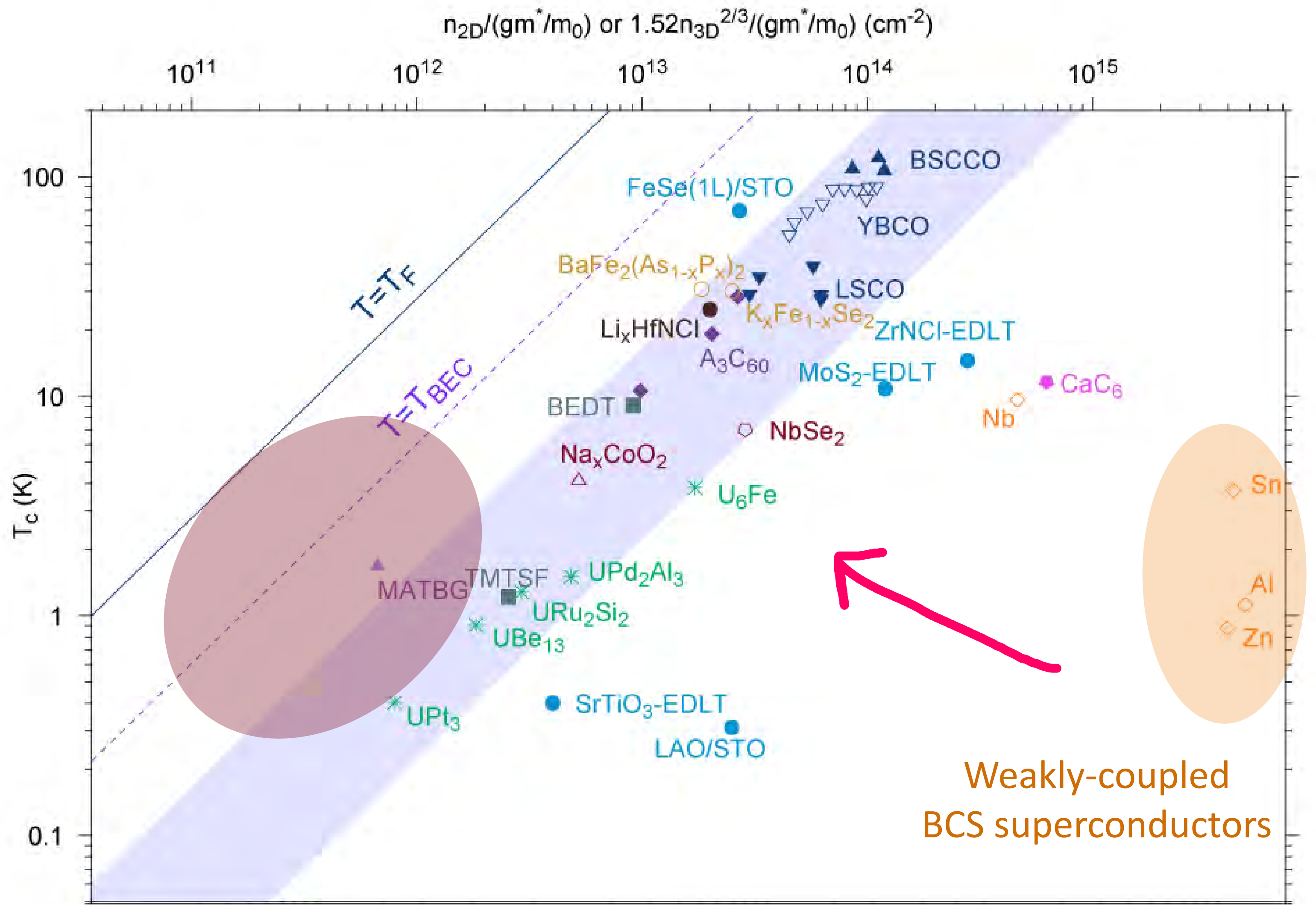
The Magic Family
of Twisted Graphene Superconductors

Jeong Min (Jane) Park

2024 Theory Winter School

parkjane@mit.edu

Unexplored regime of superconductivity



Strongly-coupled superconductors

Outline

- 2-dimensional twisted materials for correlated physics
  - Magic-angle twisted bilayer graphene
- Magic-angle twisted trilayer graphene
- The magic family
- Outlook

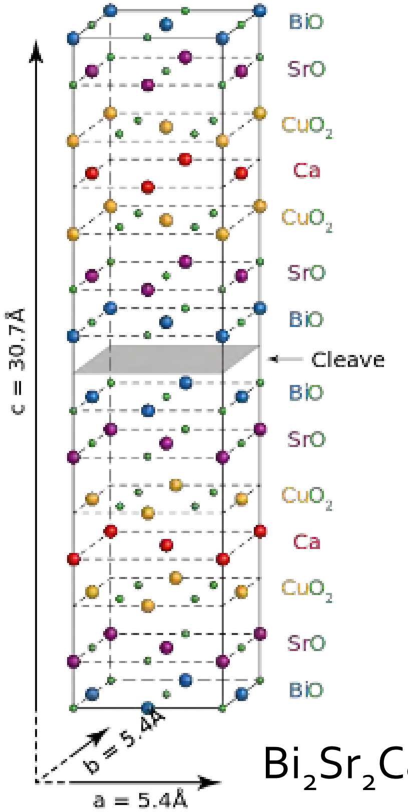
How to study strongly correlated physics?

<u>Quantum Materials</u>

Lattice scale ~ **few Å**

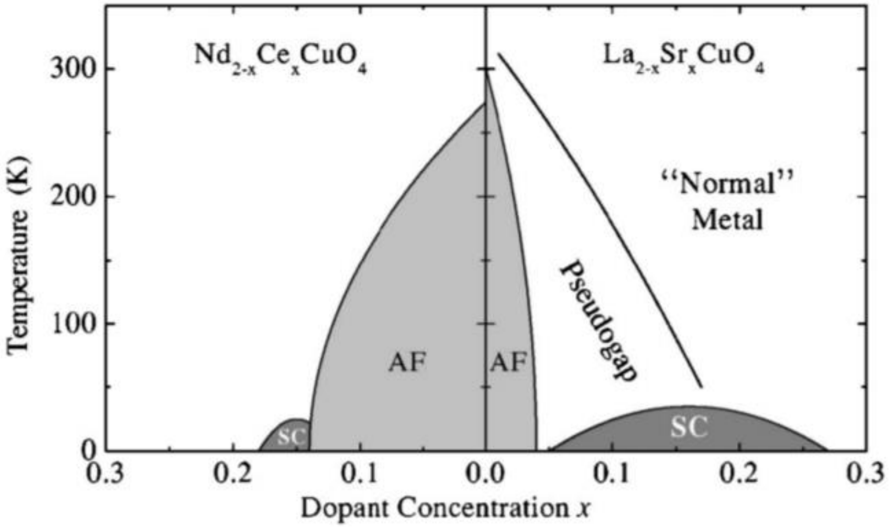
Temperature scale

~ **100-1,000 Kelvin**



$Bi_2Sr_2Ca_nCu_{n+1}O_{2n+6-d}$

"Doping"



← *electron* -doping   *hole* -doping →

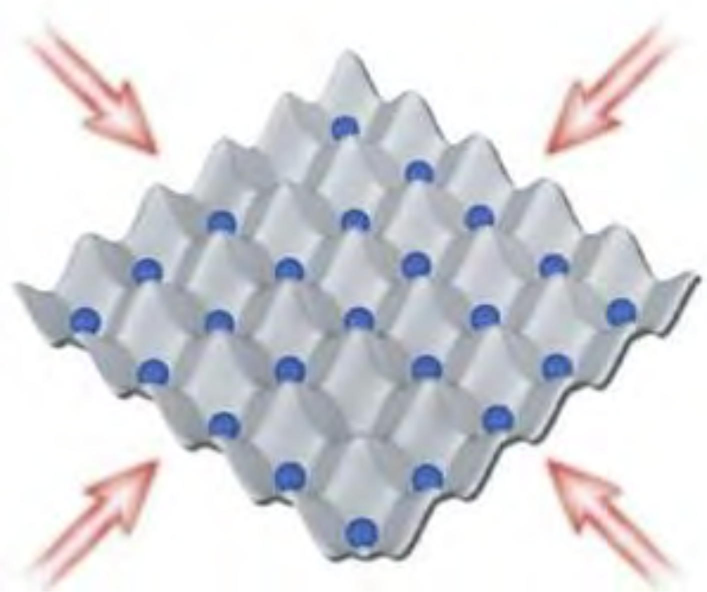
Damascelli, Hussain & Shen, *Rev. Mod. Phys.* (2003)

<u>Cold Atoms Optical Lattices</u>

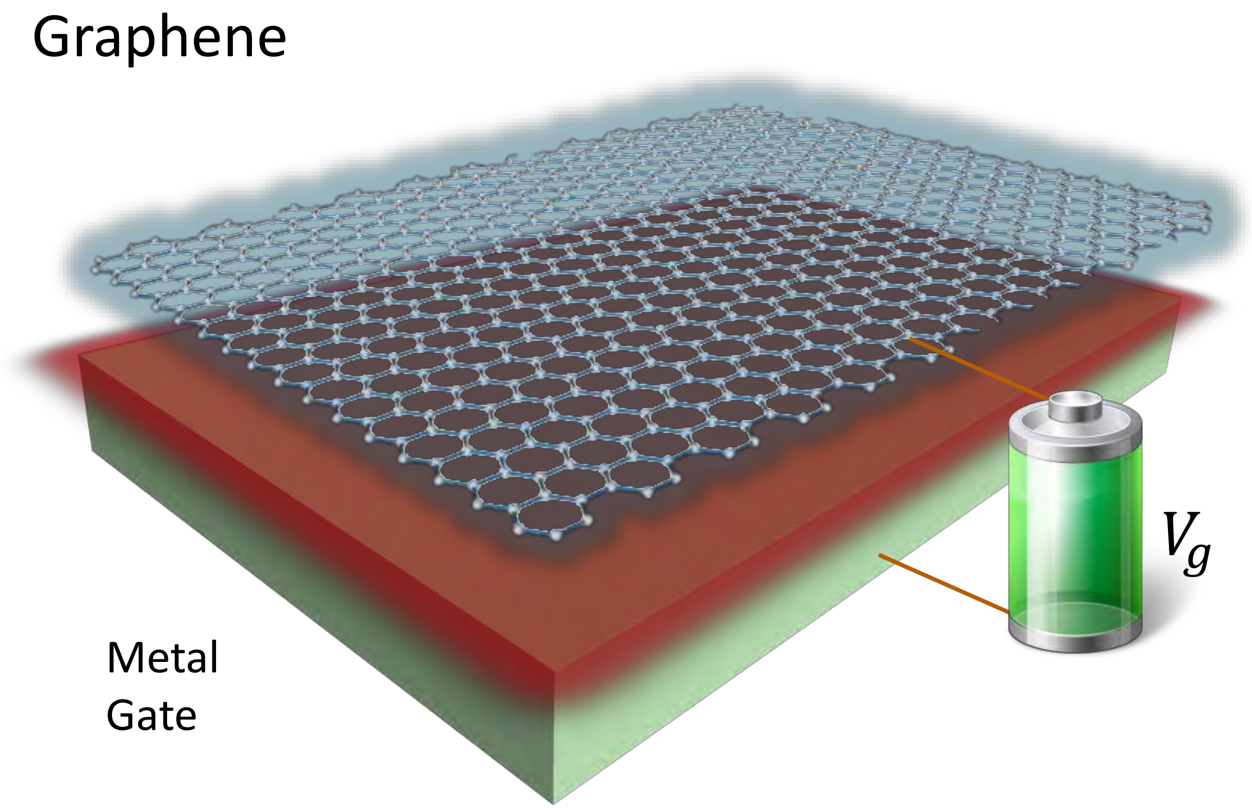
Length scale ~ **1 micron**

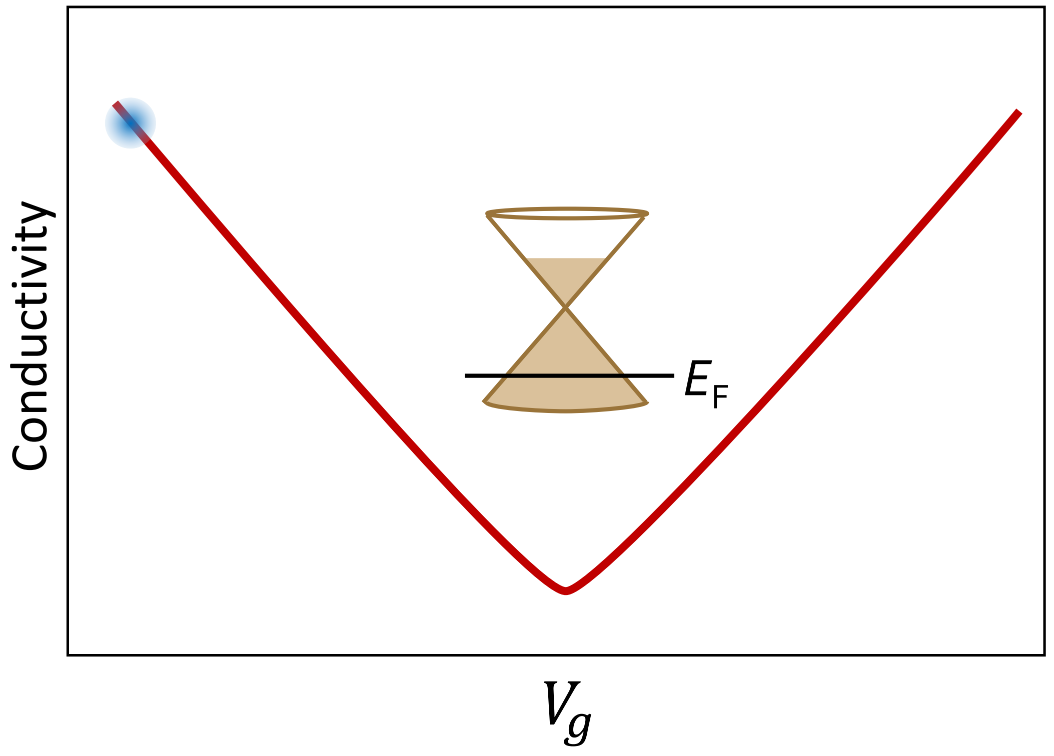
Temperature scale

~ **0.1-1 nanoKelvin**



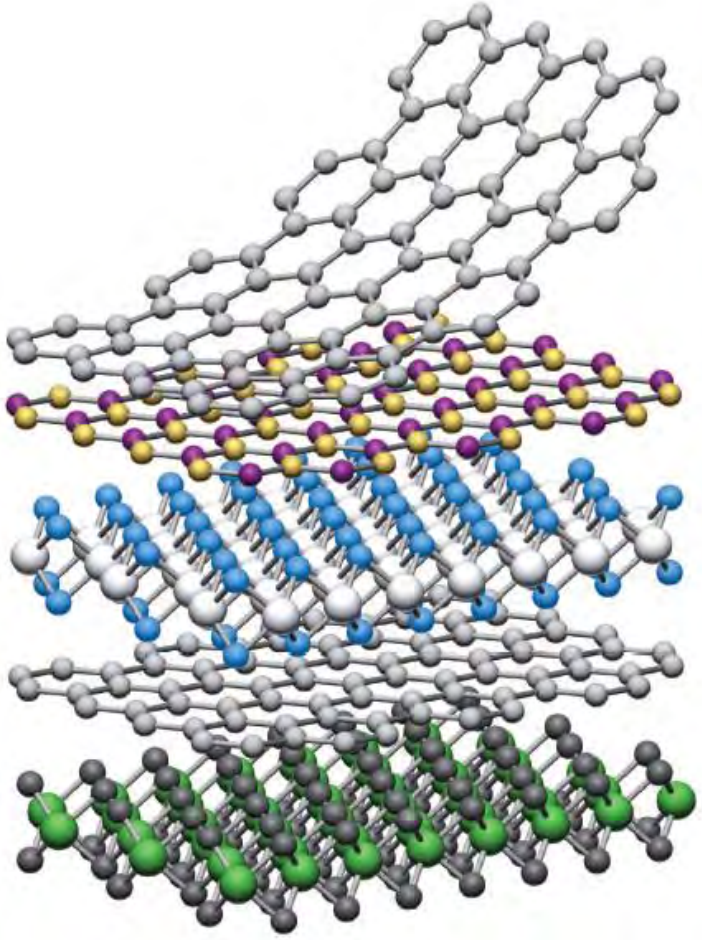
Doping tunability of 2D materials

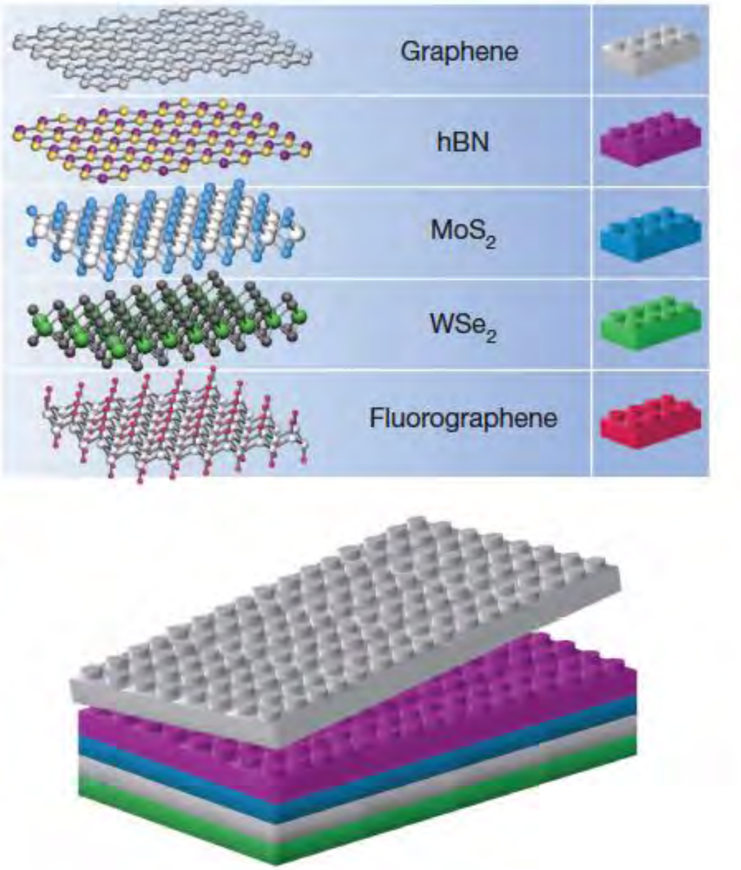




Charge density $n = CV_g/e$

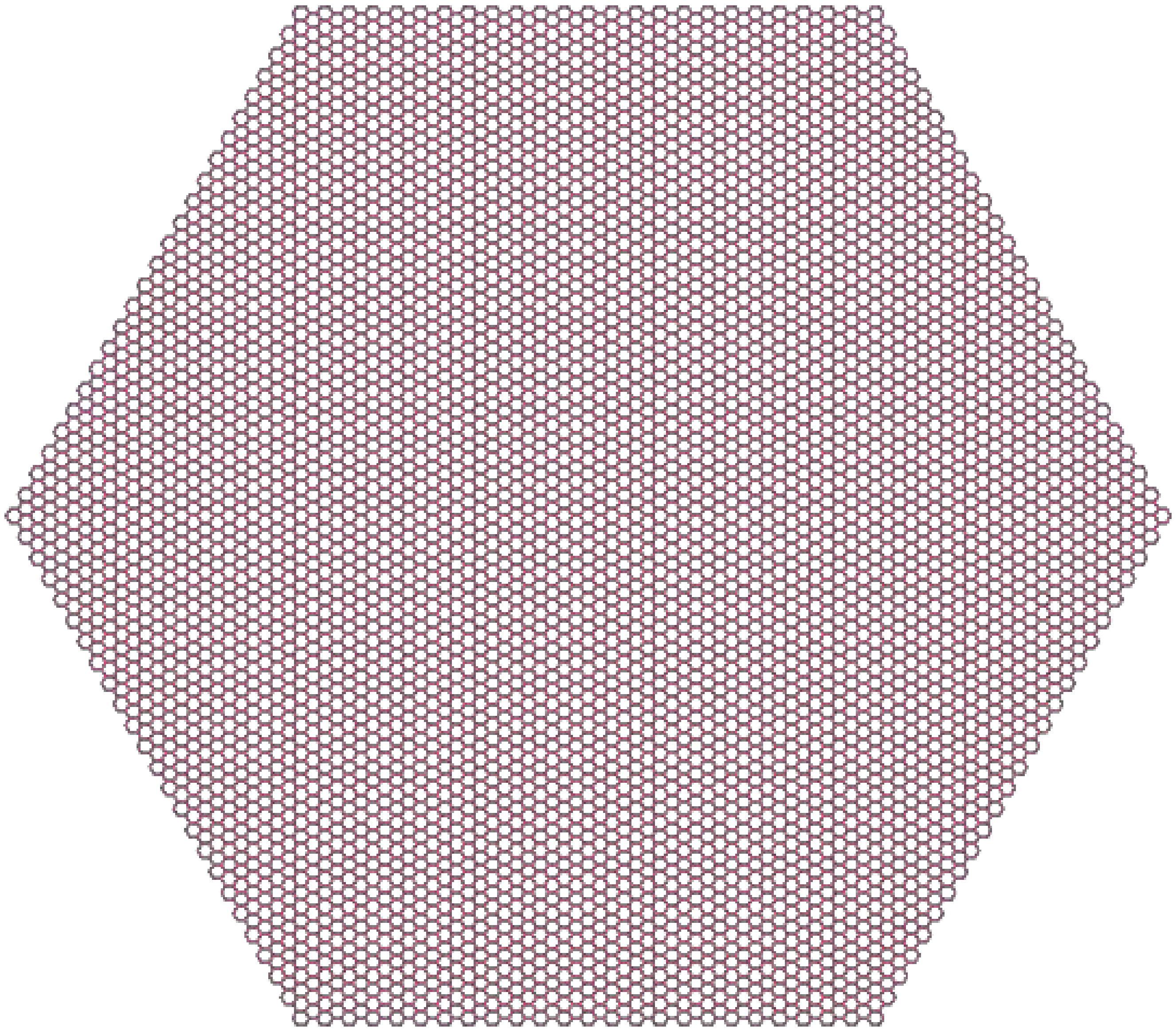
Stacking tunability of 2D materials



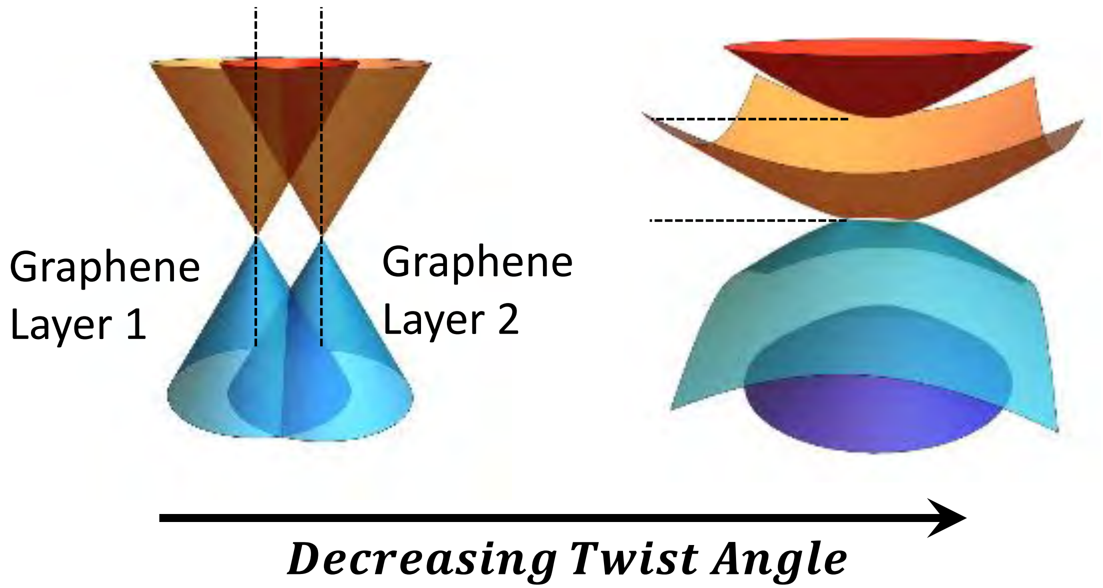


Geim & Grigorieva, Nature (2013)

Even more: twist angle!

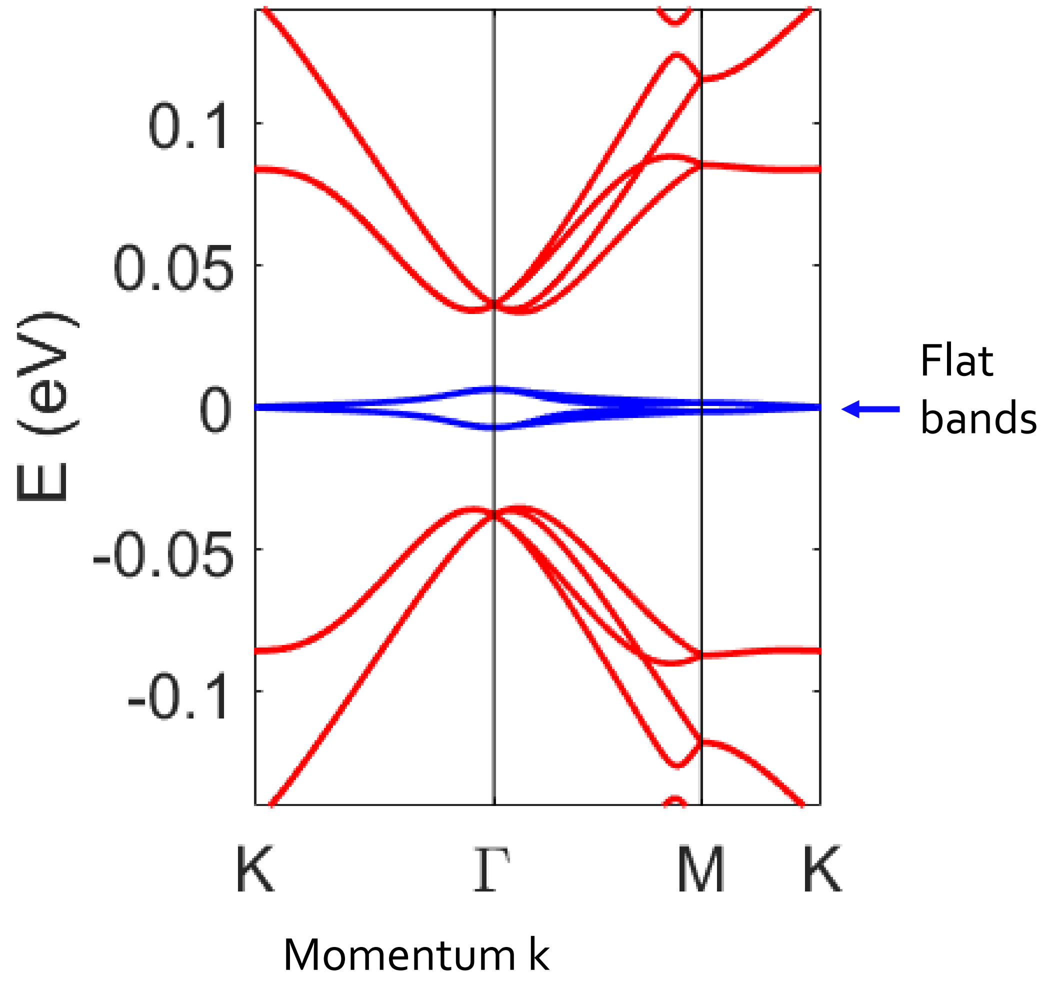


Designing flat bands



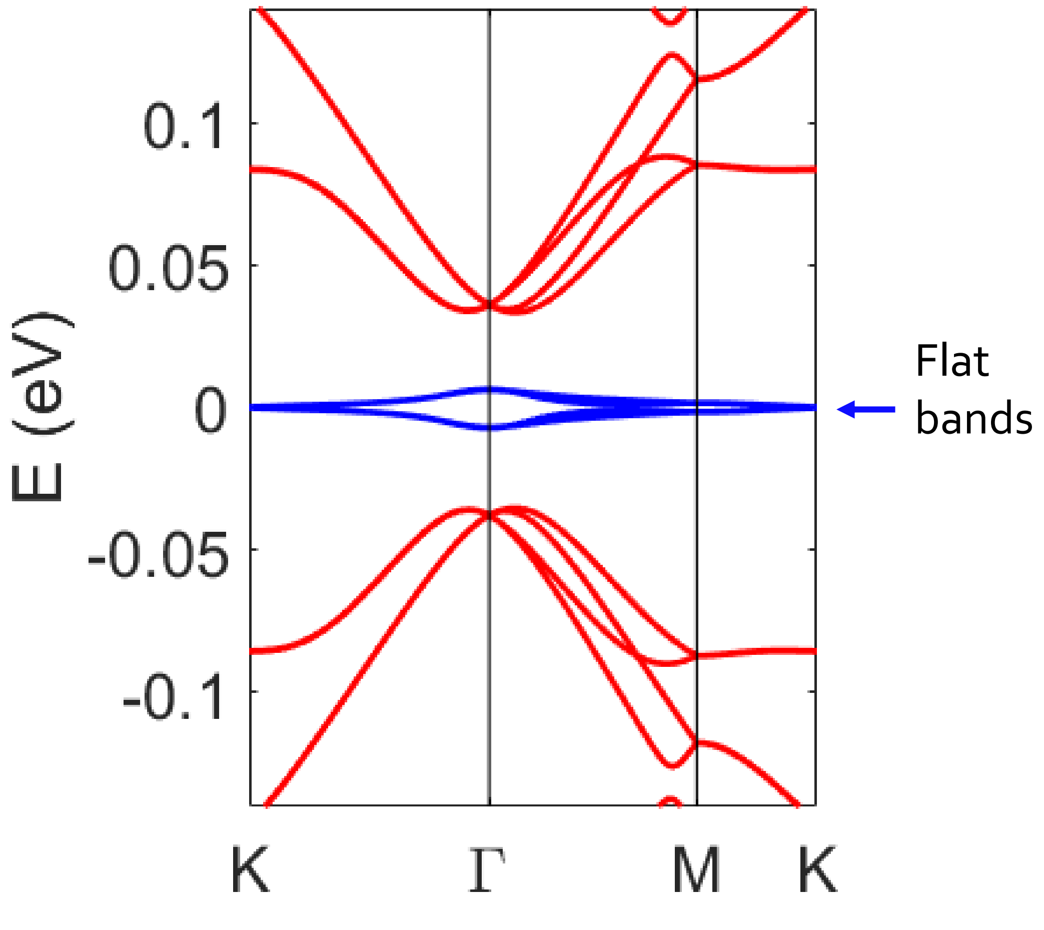
"Flat Band" condition is reached at the "Magic Angle"

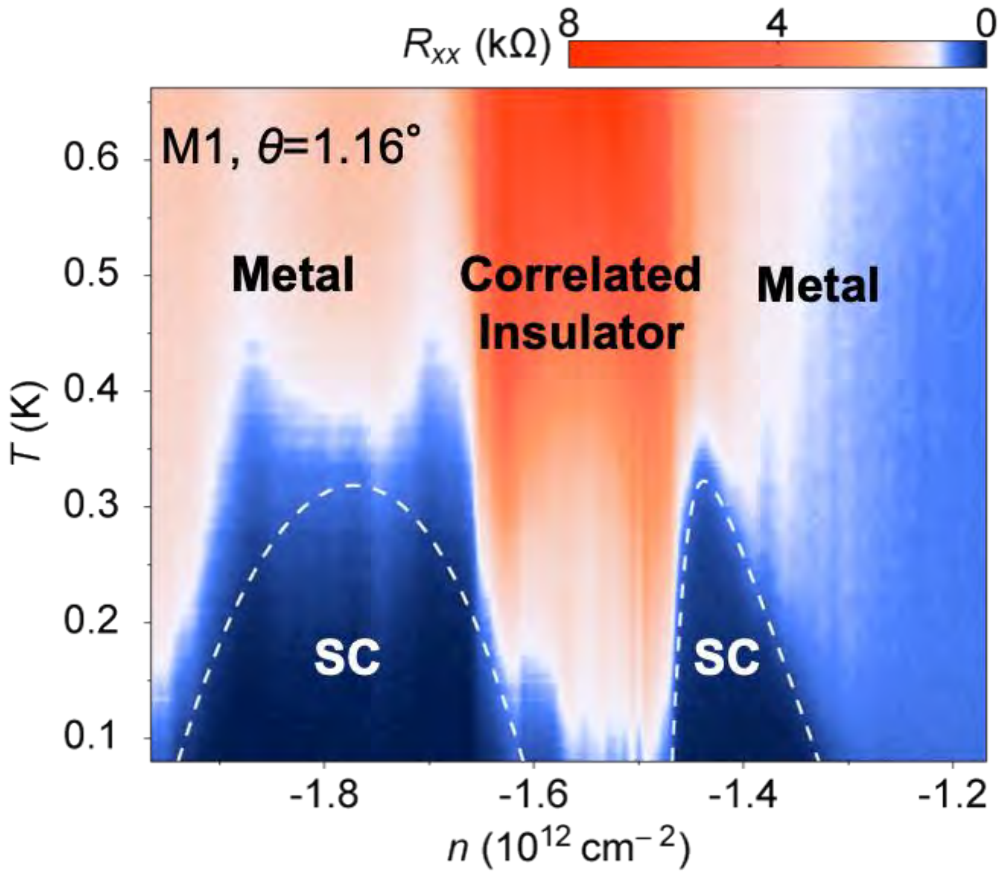
$$\boxed{\theta_{M1} \approx 1.1°}$$



Bistritzer & MacDonald, *PNAS* (2011);
Also: Li *et al. Nature. Phys.* (2010); Suarez-Morell *et al. PRB* (2010)

Superconductivity in the flat bands

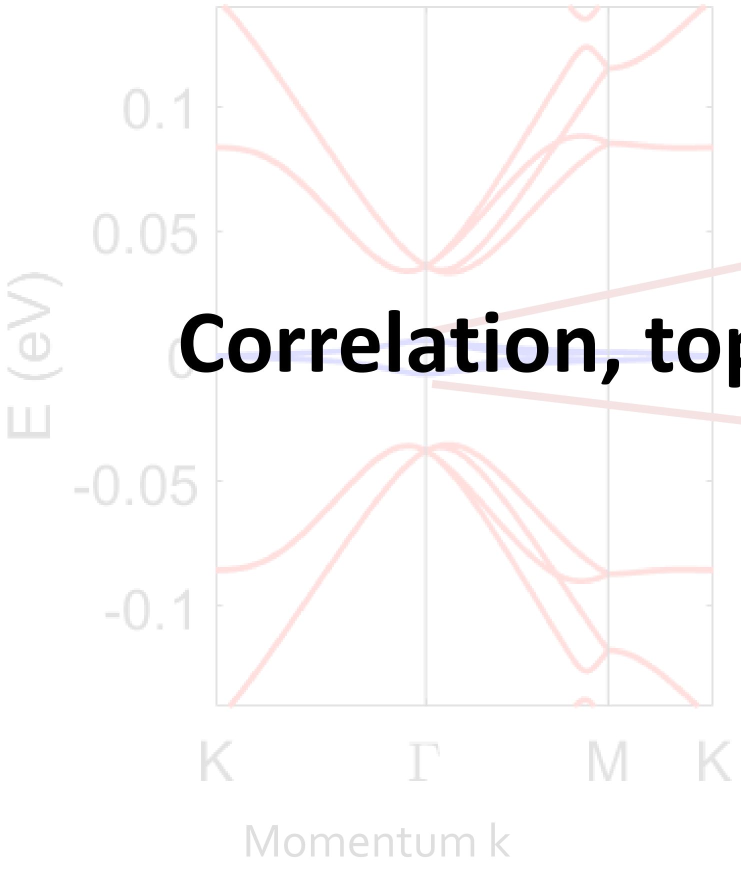


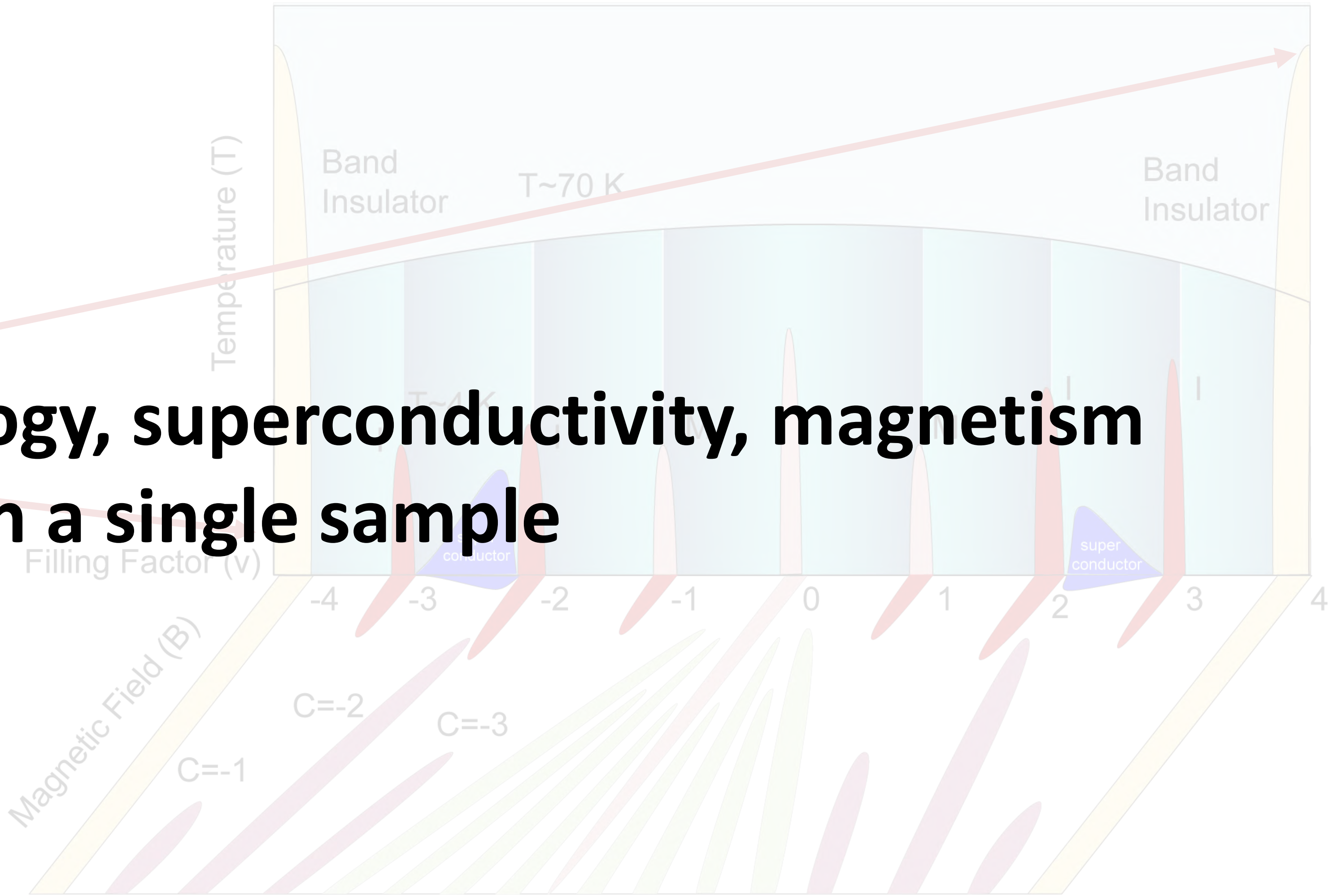


Low-density superconductor

YC, PJH *et al. Nature* **556**, 80 (2018)

So many phases in a single material



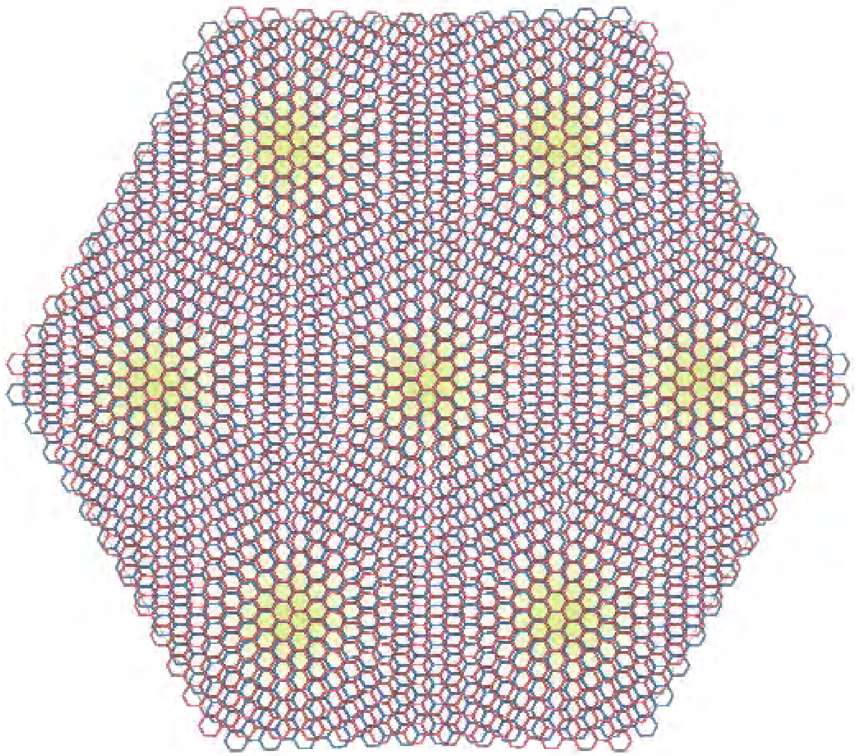


Correlation, topology, superconductivity, magnetism in a single sample

Moiré is different

<u>Moiré Quantum Matter</u>

Moiré length ~ **10nm**



Correlated Insulators
(MATBG, ABC/hBN, Twisted Bi-Bi, TMD moiré heterostructures, etc)

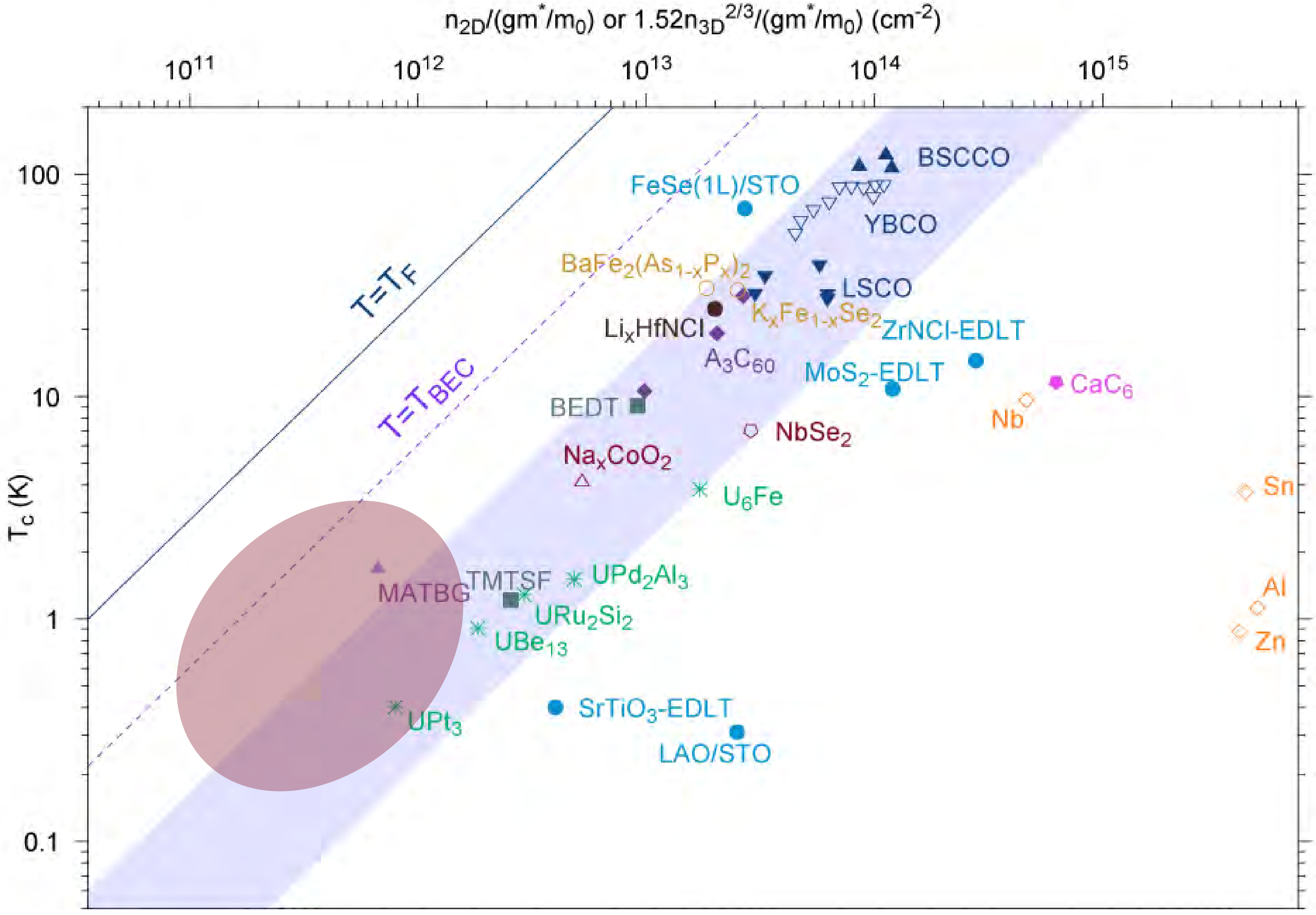
Robust Superconductivity
(MATBG, signatures in other systems)

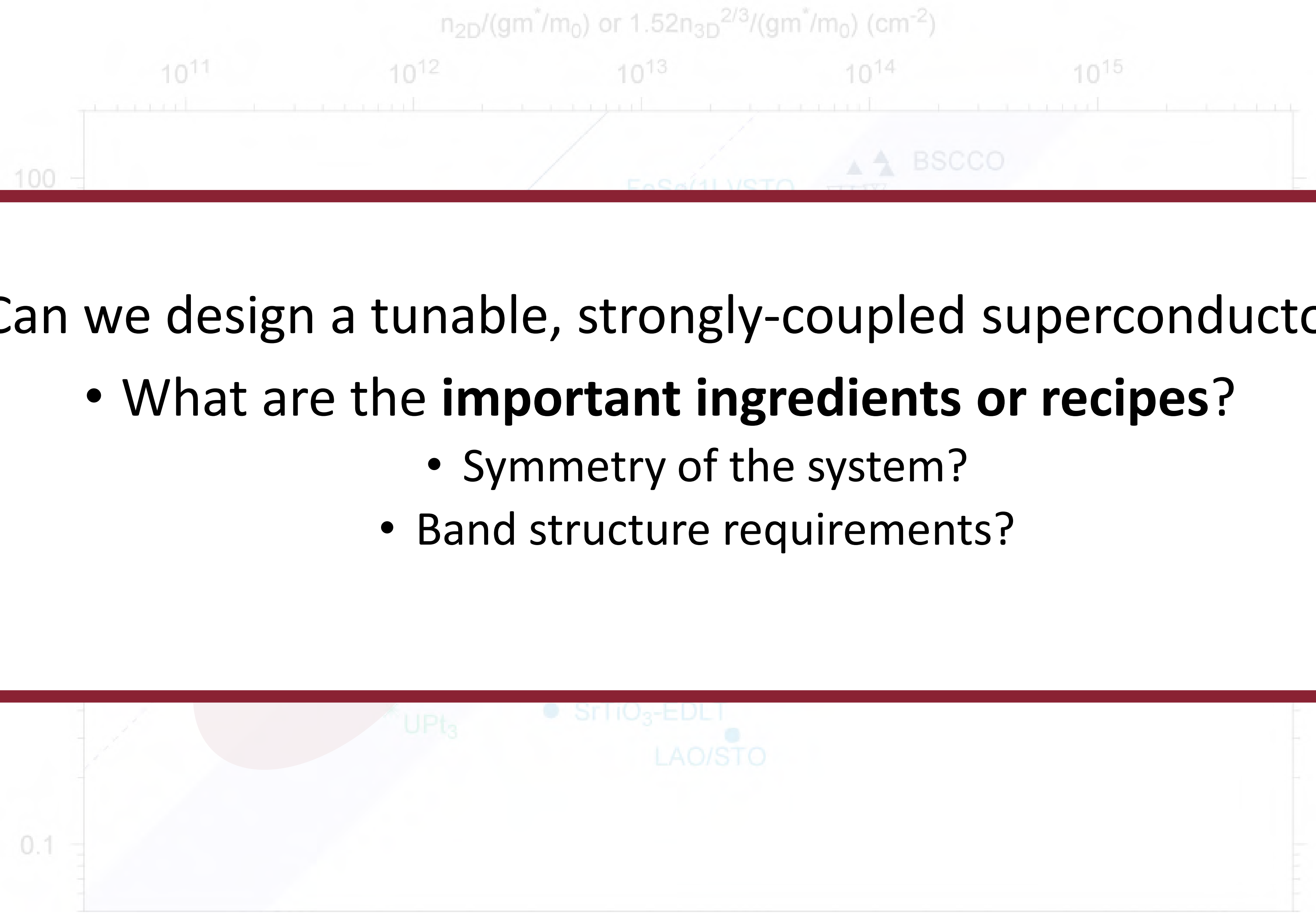
Topological Phases
(MATBG, MATBG/hBN, ABC/hBN, Twisted Bi-Bi, Twisted Mono-Bi, etc))

Magnetism
(MATBG/hBN, ABC/hBN, Twisted Mono-Bi)

Moiré Ferroelectricity
(Twisted BN/BN, BLG/BN, Twisted TMD/TMD)

Moiré is different for superconductivity?

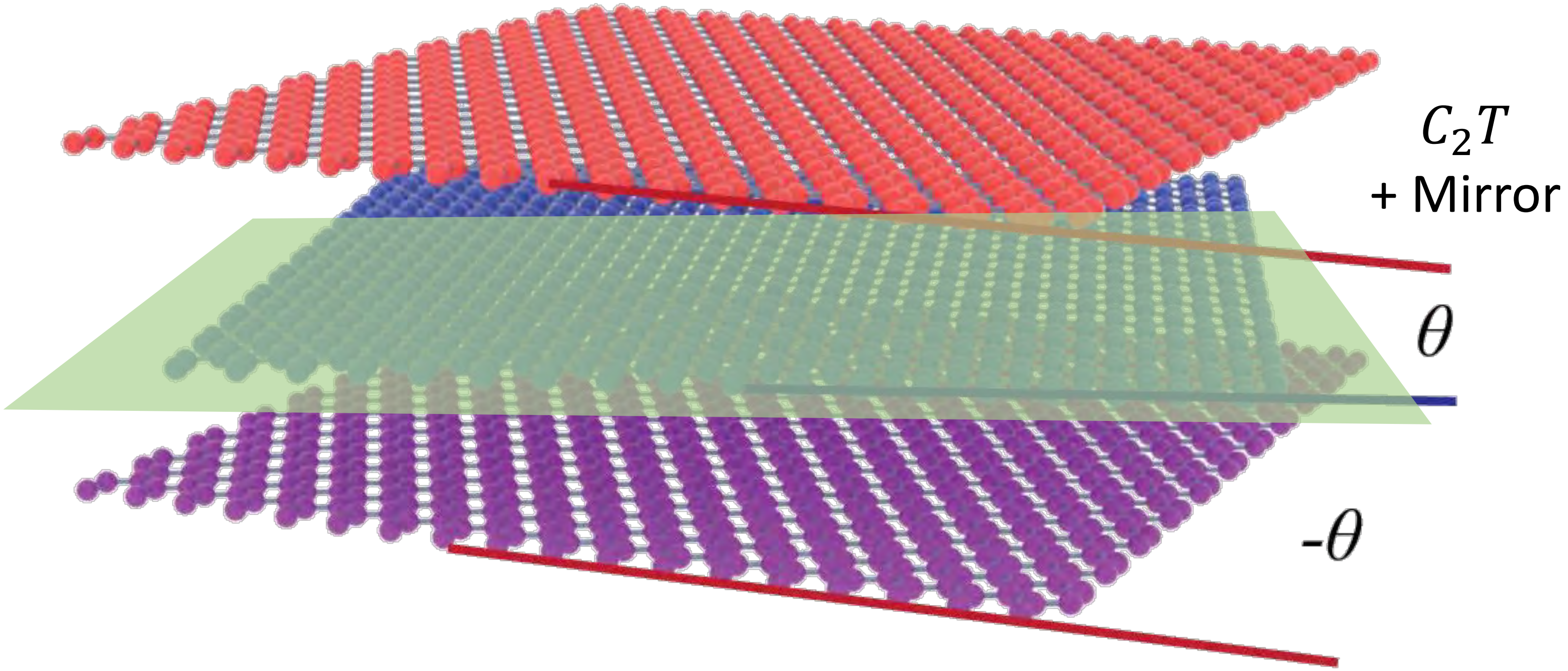




- Can we design a tunable, strongly-coupled superconductor?
- What are the **important ingredients or recipes**?
  - Symmetry of the system?
  - Band structure requirements?

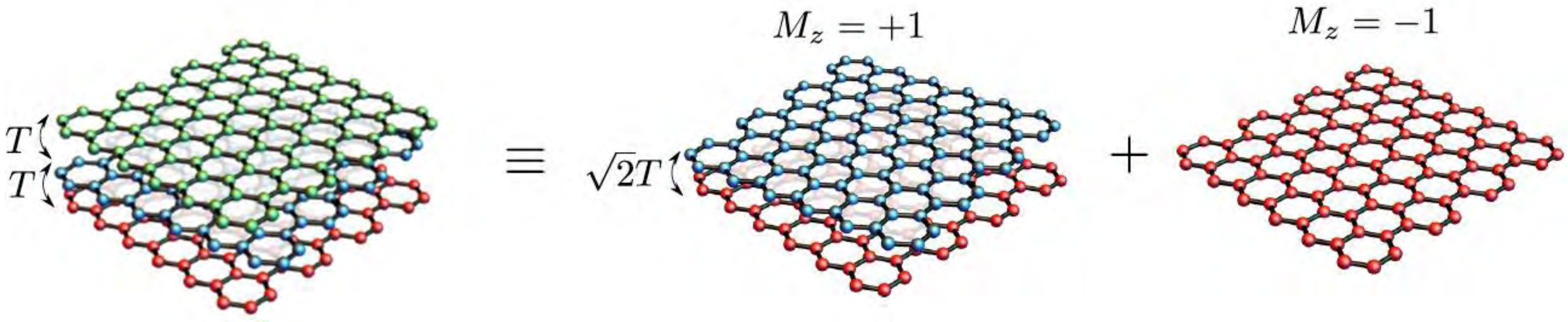
- 2-dimensional materials for strongly correlated physics
  - Magic-angle twisted bilayer graphene
- Magic-angle twisted trilayer graphene
- The magic family
- Outlook

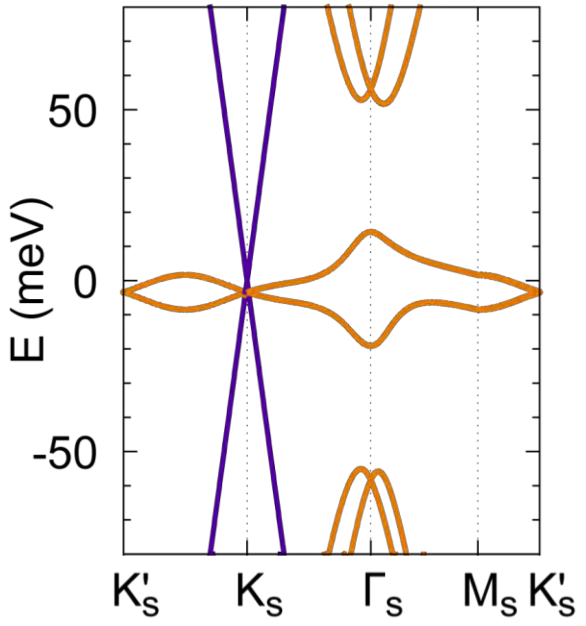
Magic-angle twisted trilayer graphene (MATTG)



<u>JMP</u> et al. *Nature* **590**, 249 (2021)

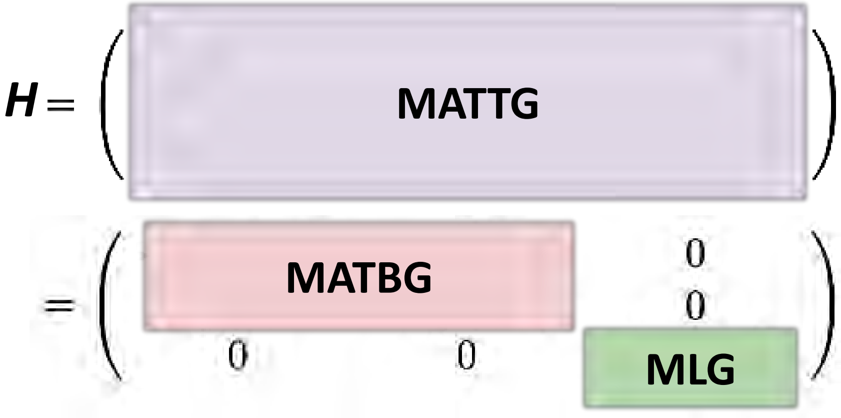
Magic-angle twisted trilayer graphene (MATTG)





C_2T → protects the Dirac points

Mirror → protects the separate Dirac band



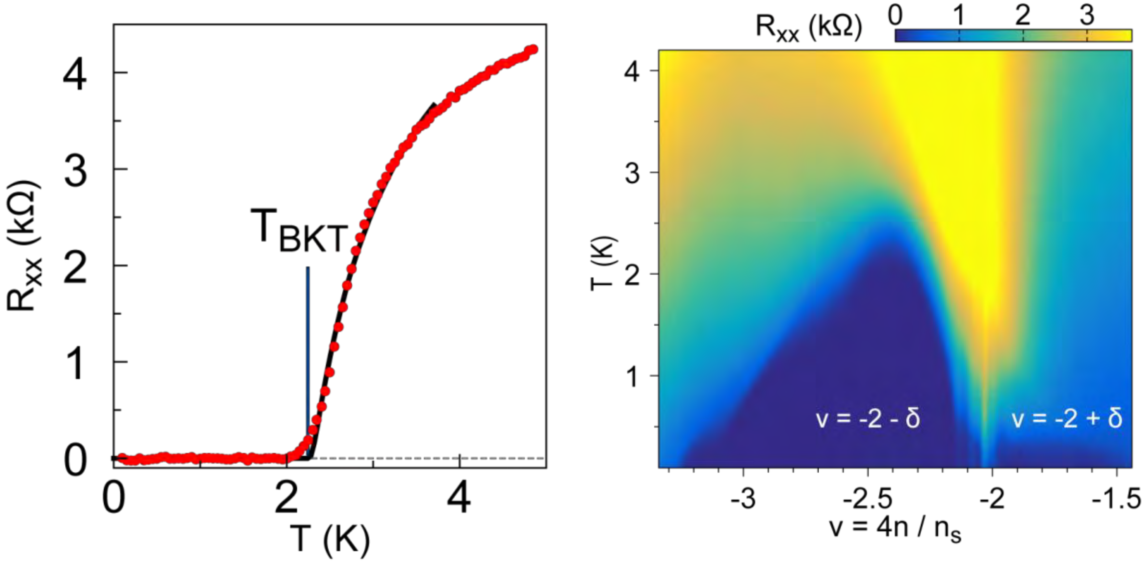
$$\theta_{MATTG} = \theta_{MATBG} \times \sqrt{2} \approx 1.1° \times \sqrt{2} \approx 1.56°$$

Khalaf, Vishwanath et al. *Phys. Rev. B* **100**, 085109 (2019)

JMP et al. *Nature* **590**, 249 (2021)

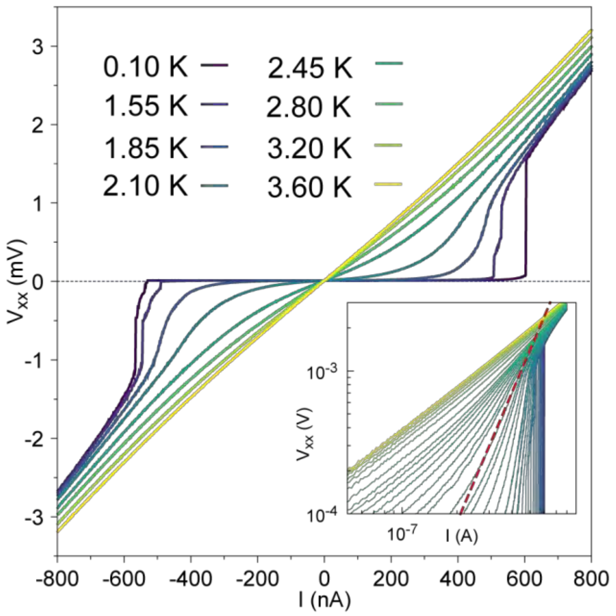
MATTG is a robust superconductor

1. Zero resistance

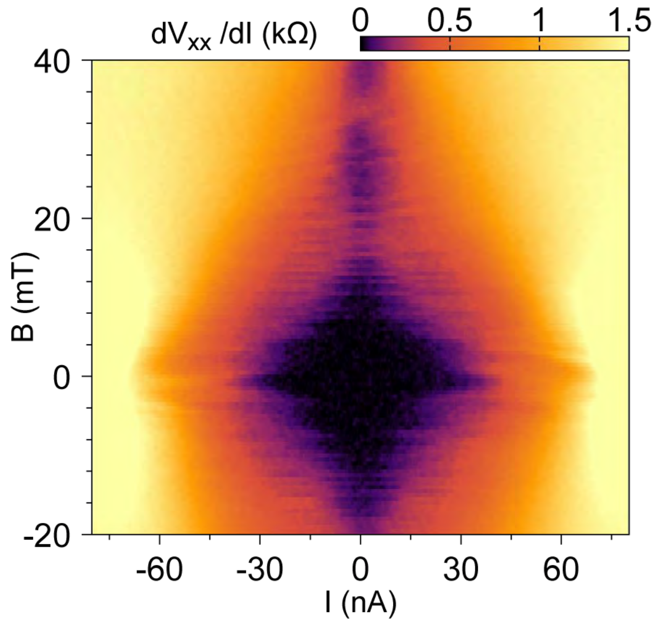


$$T_{C,\,50\%} \sim 2.9\ K$$

2. Sharp Switching V-I characteristics



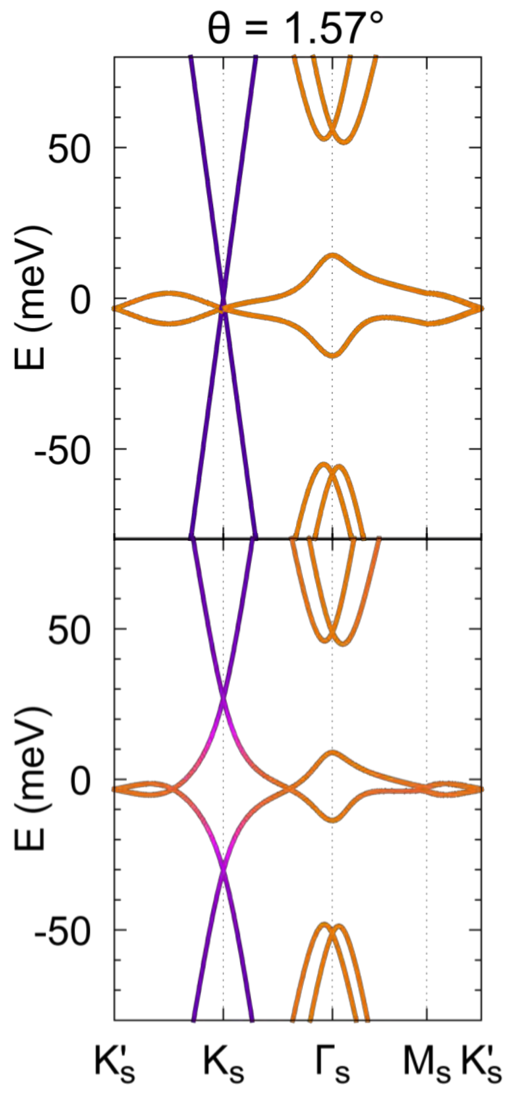
3. Josephson phase coherence

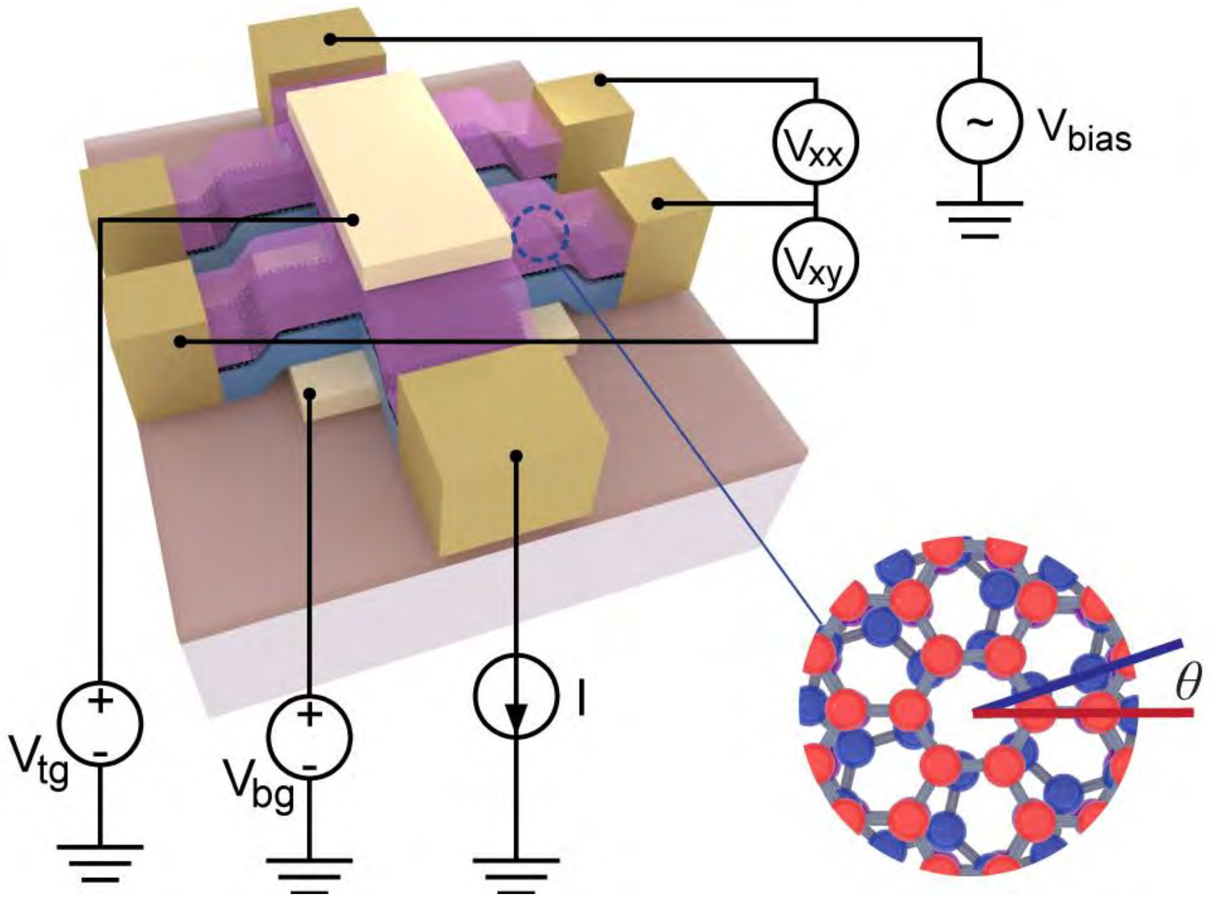


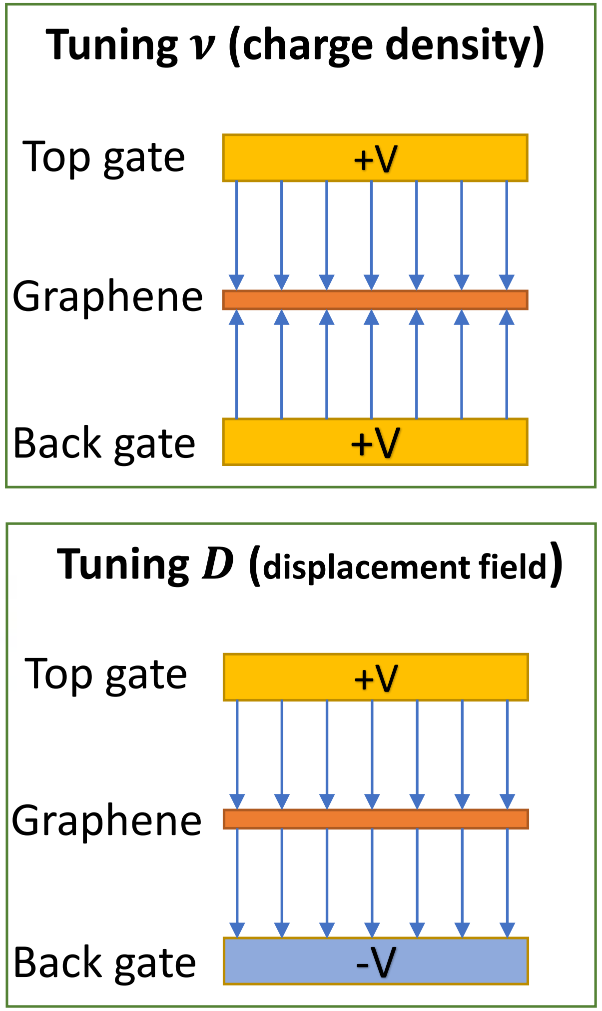
MATTG is a robust moiré superconductor!

JMP et al. *Nature* **590**, 249 (2021)

Further tunability: band structure

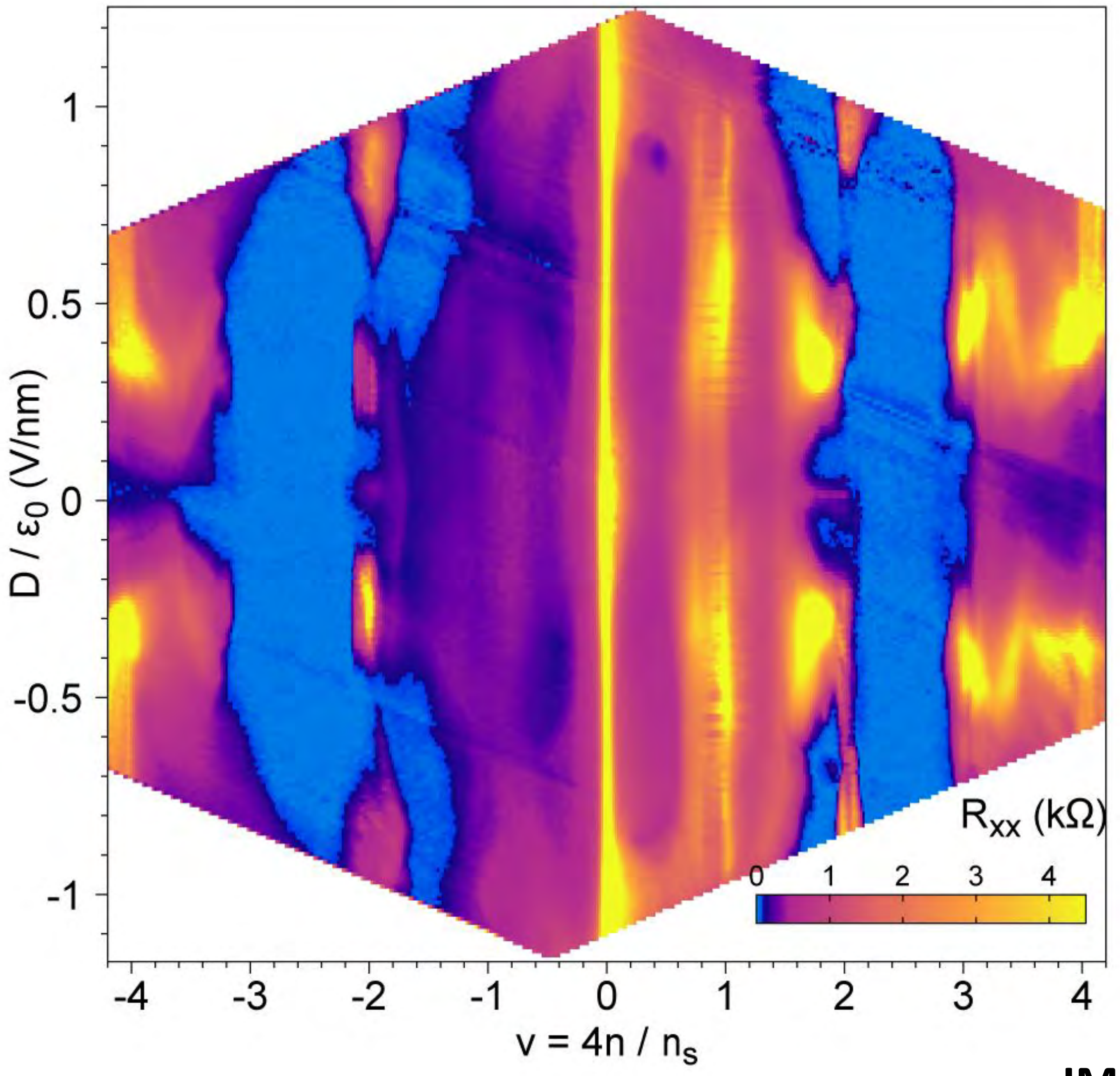






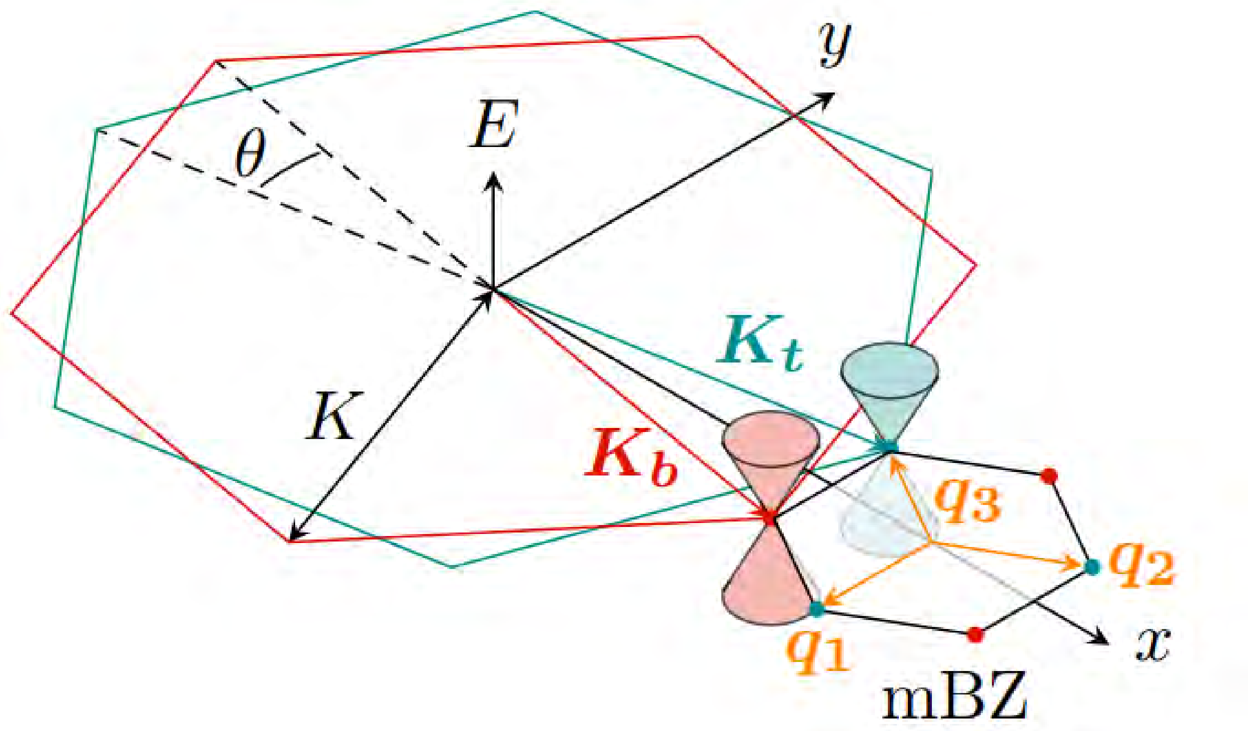
Band structure can be tuned *in situ*
with dual-gate geometry, in addition to doping

ν - D phase space



<u>**JMP**</u> et al. *Nature* **590**, 249 (2021)

Counting electrons in the new BZ



2-fold spin DOF

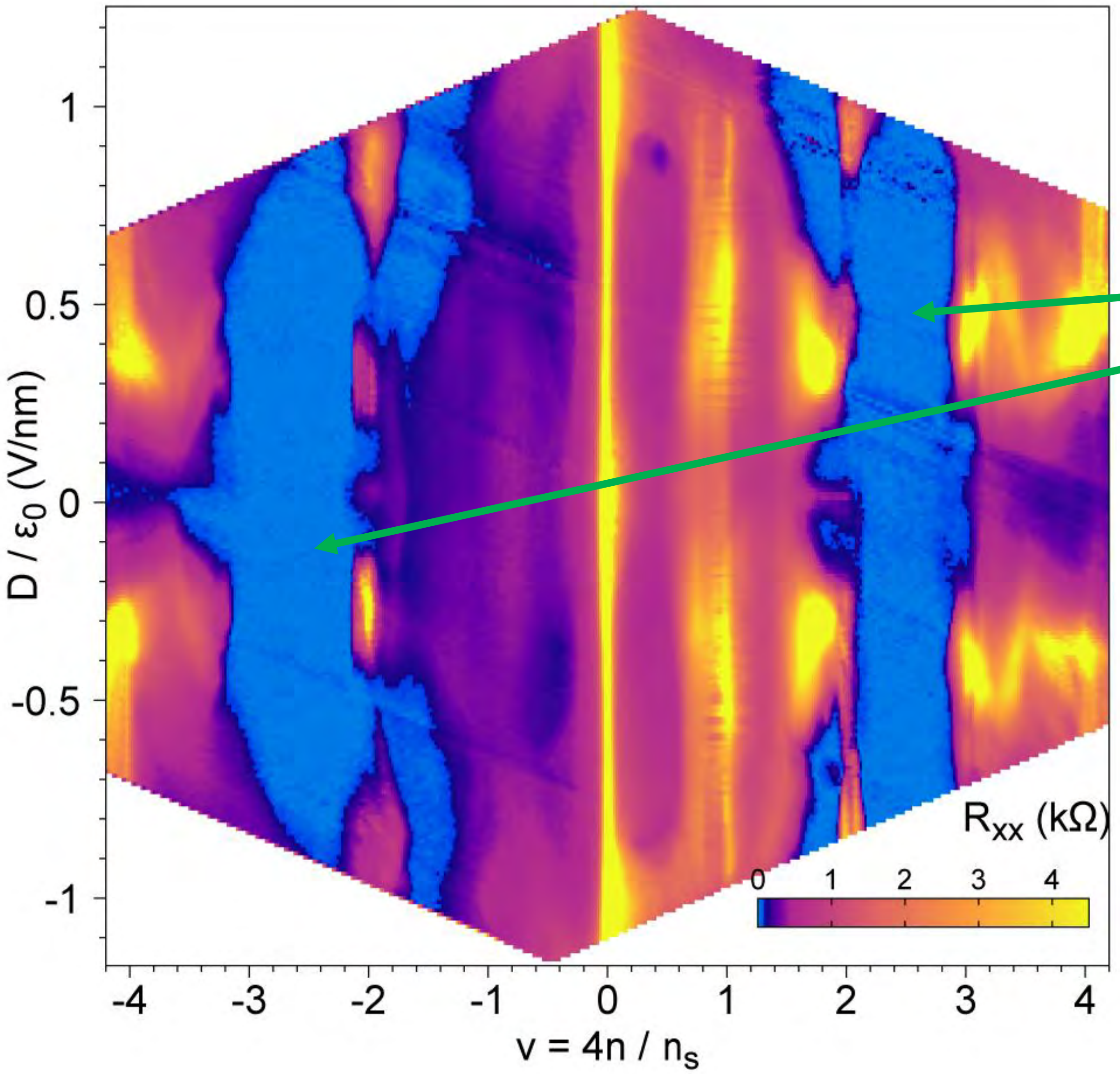
+

2-fold valley DOF

4-fold spin × valley **"Flavors"**

4 electrons per moiré unit cell
to **fill each flat band**

ν - D phase space reveals tunable SC

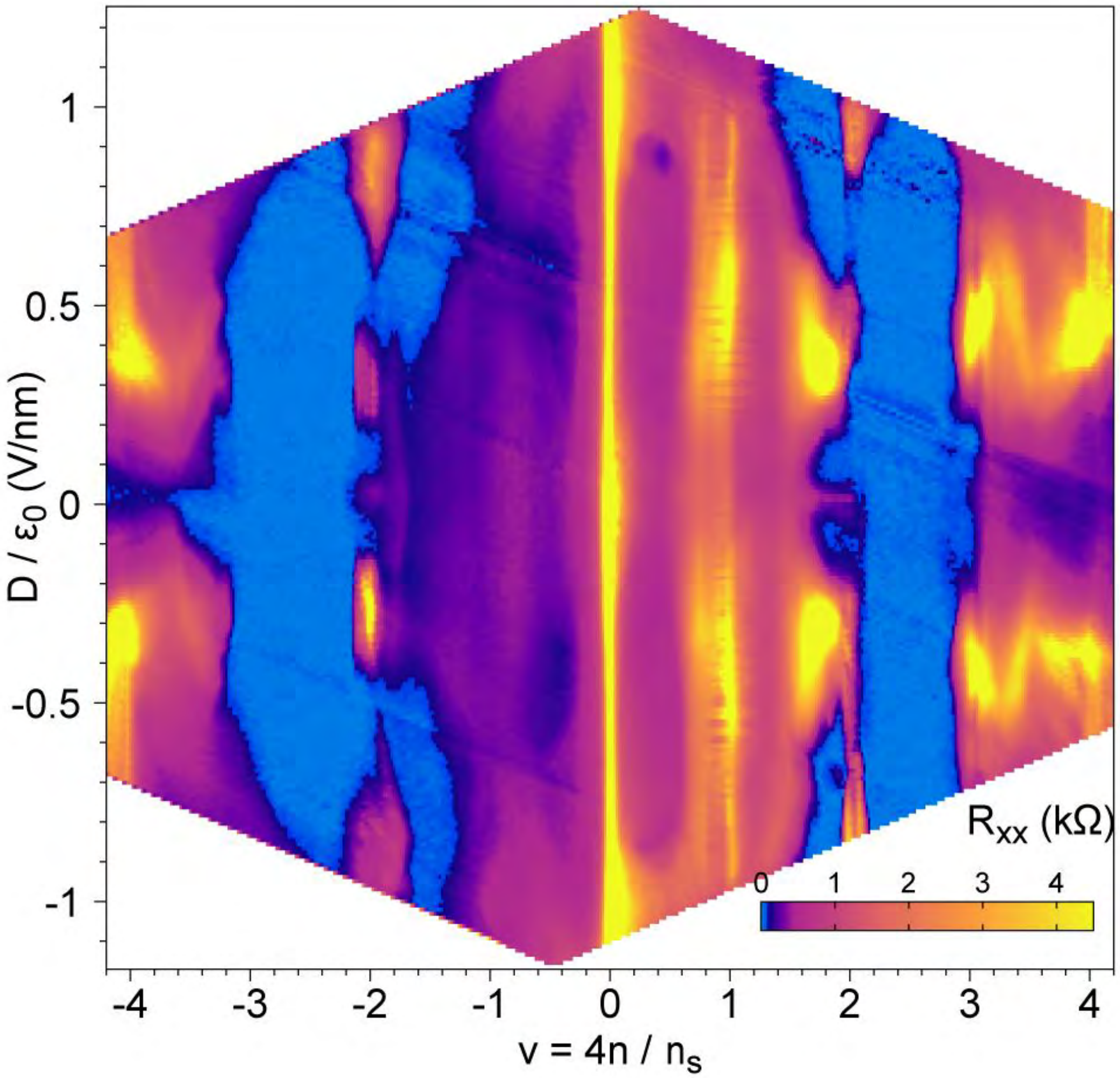


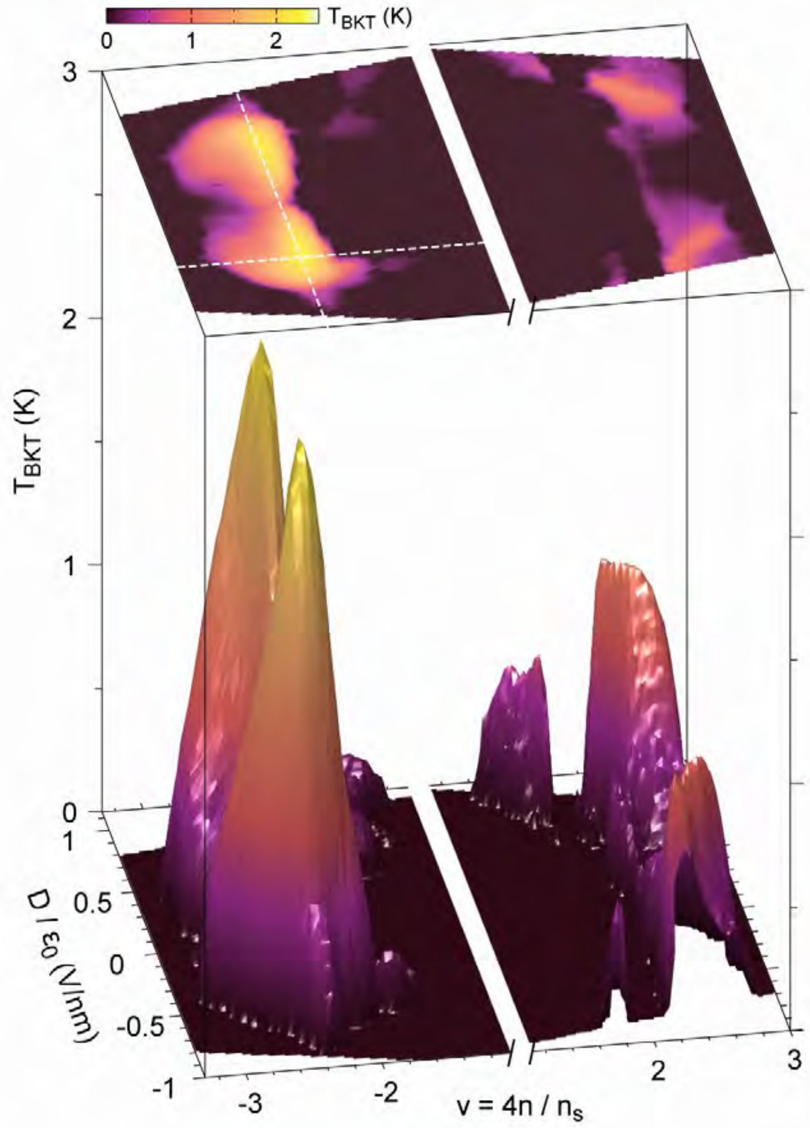
Blue: Superconductivity

Superconductivity exhibits a strong dependence on both ν and D

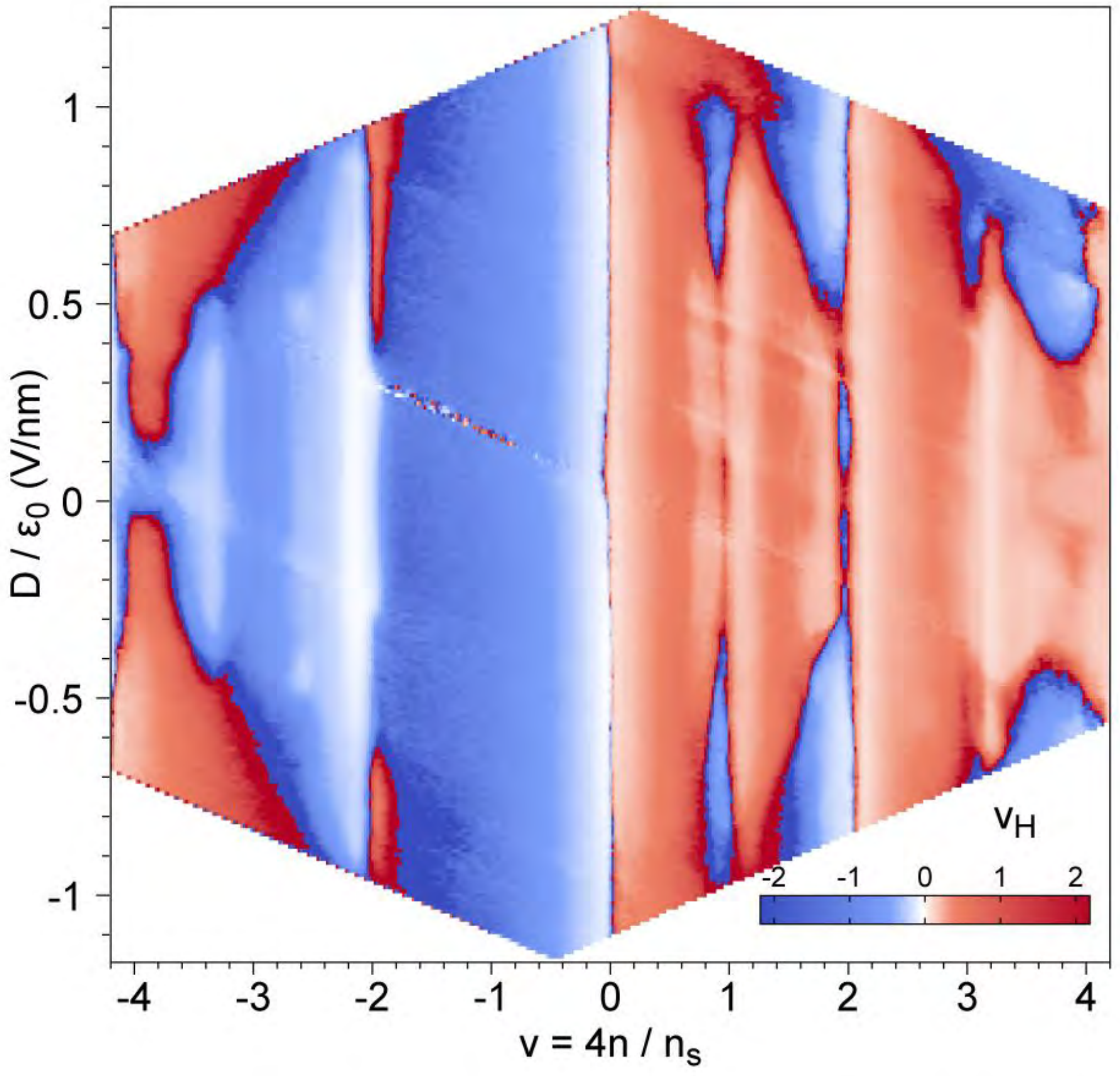
<u>JMP</u> et al. *Nature* **590**, 249 (2021)

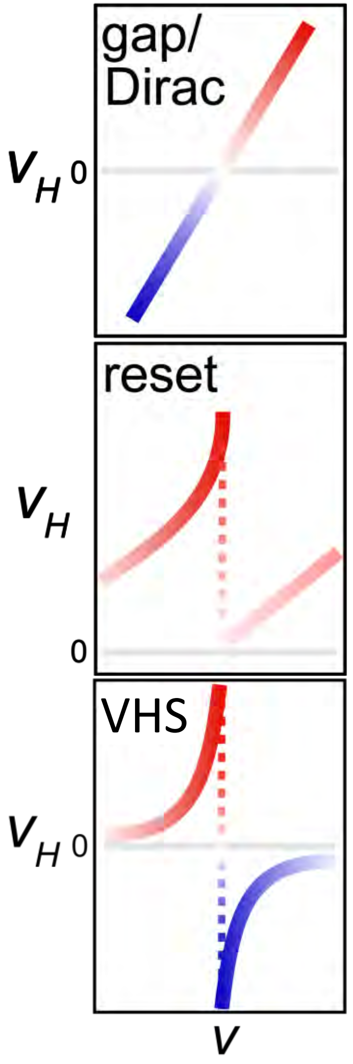
Tunable superconducting strength





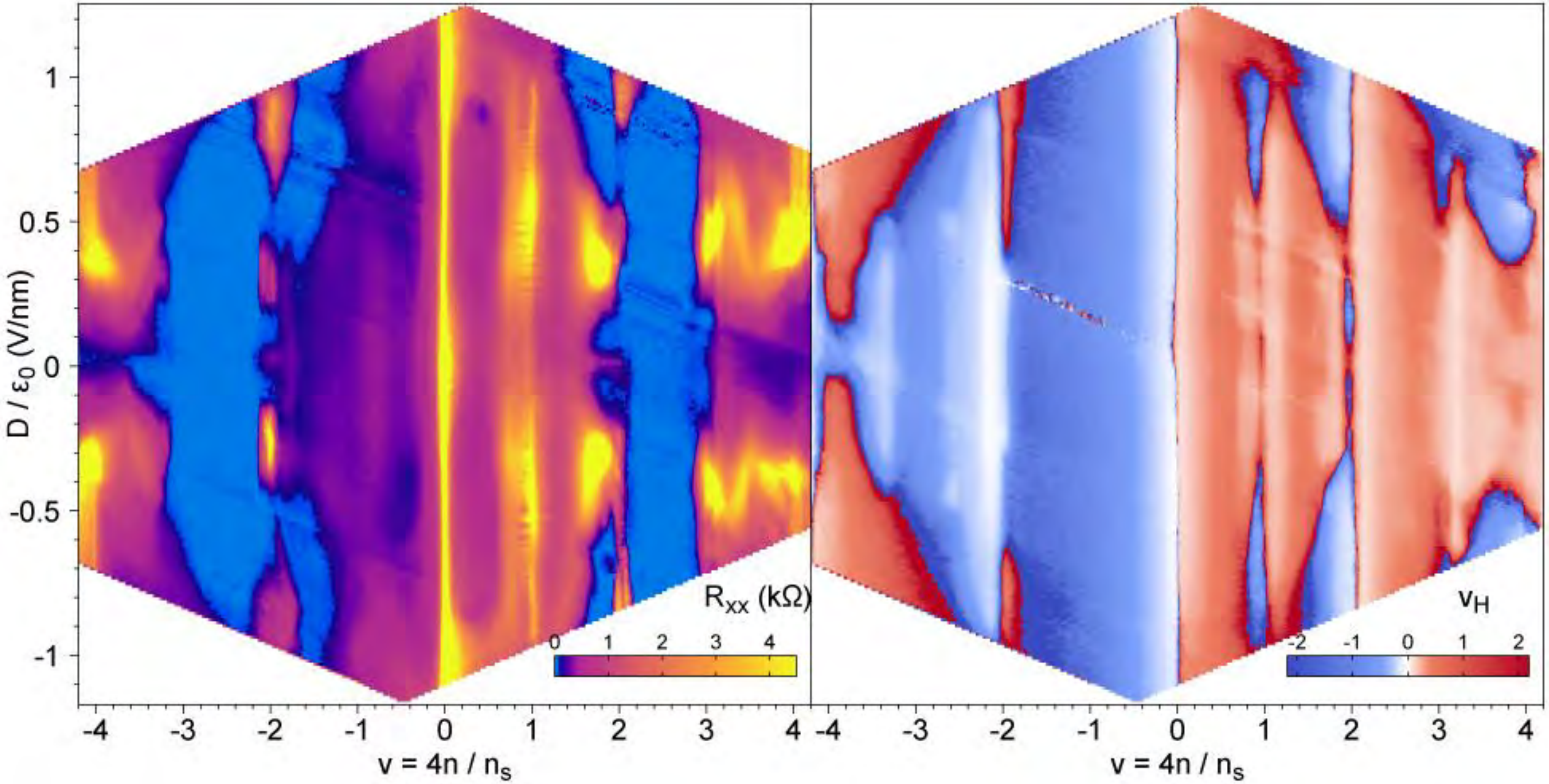
Hall density reveals Fermi surfaces





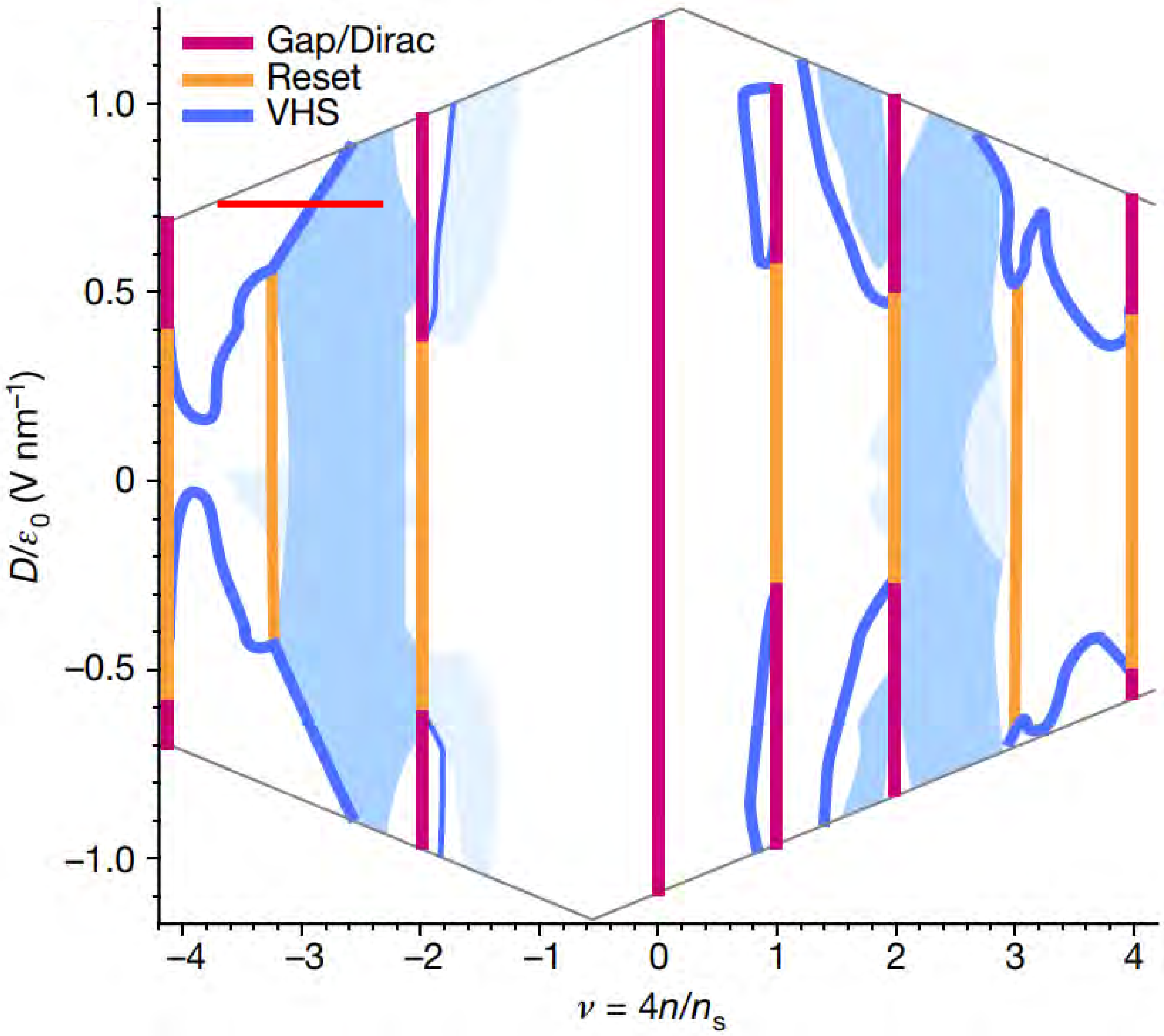
JMP et al. *Nature* **590**, 249 (2021)

Striking similiarities



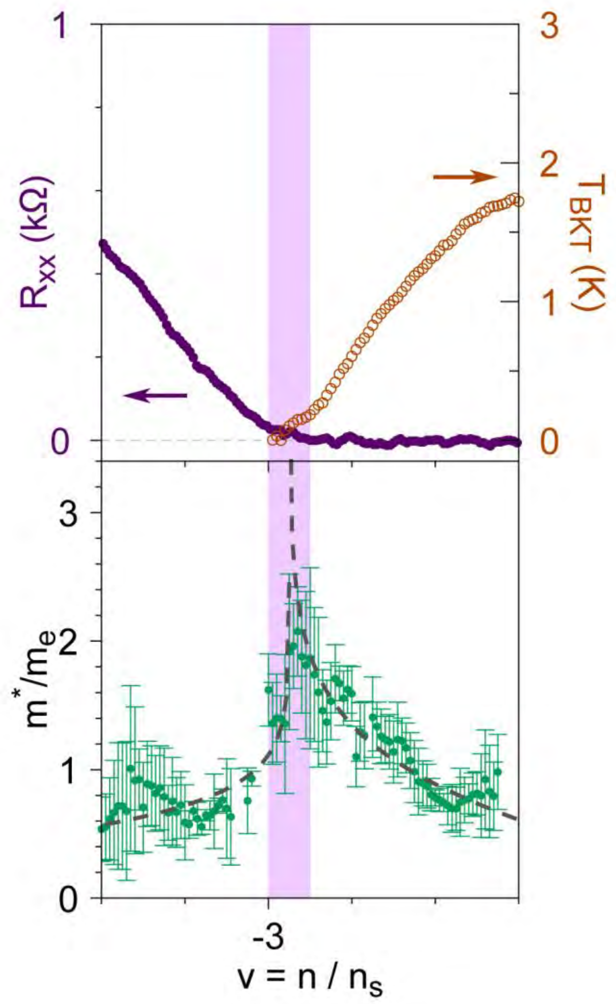
<u>JMP</u> et al. *Nature* **590**, 249 (2021)

Phase space map reveals unusual SC



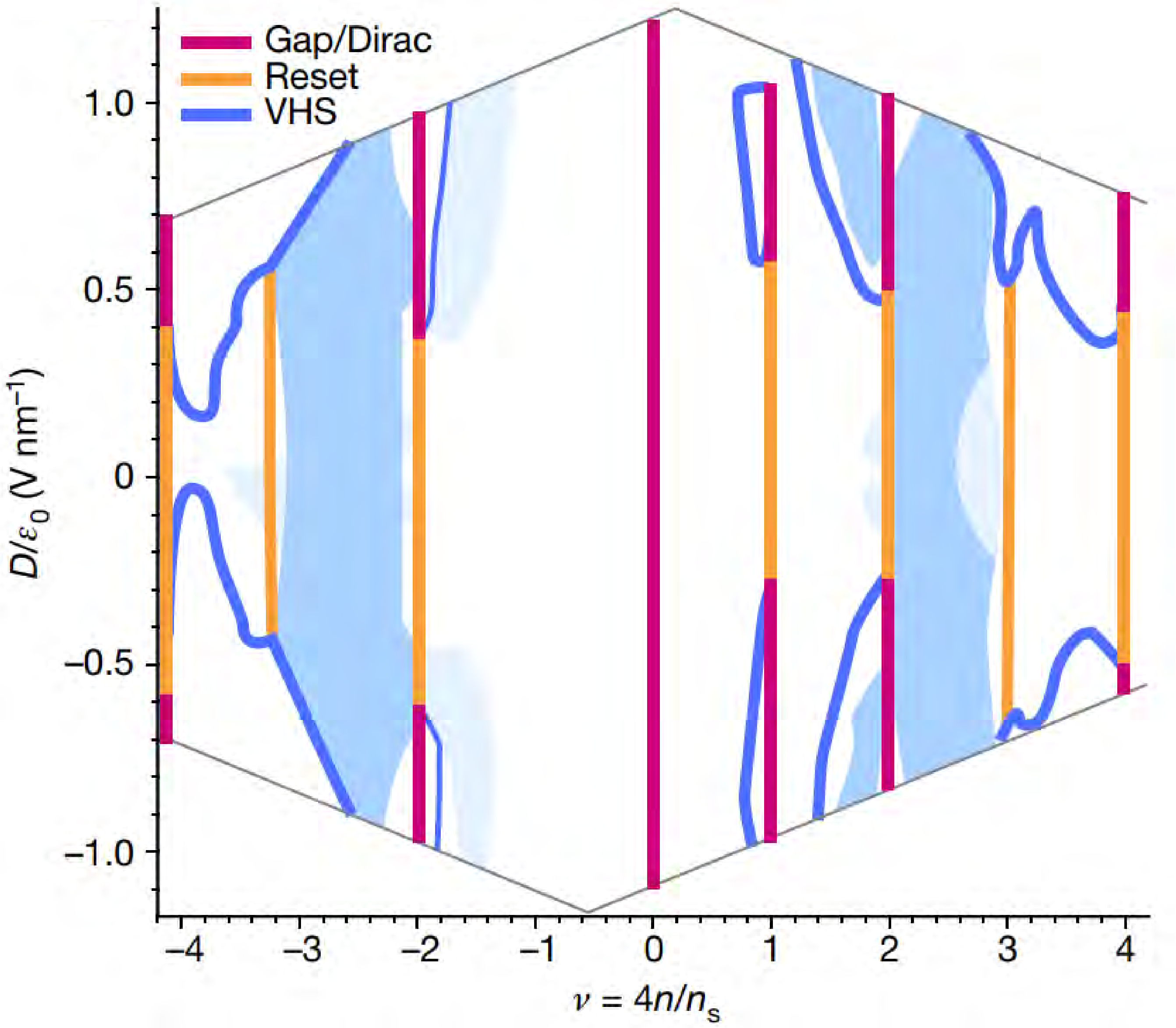
Supe… …y VHS

Opp… …3CS
supe…
(BCS … Tc)



JMP et al. *Nature* **590**, 249 (2021)

What forms superconductivity?

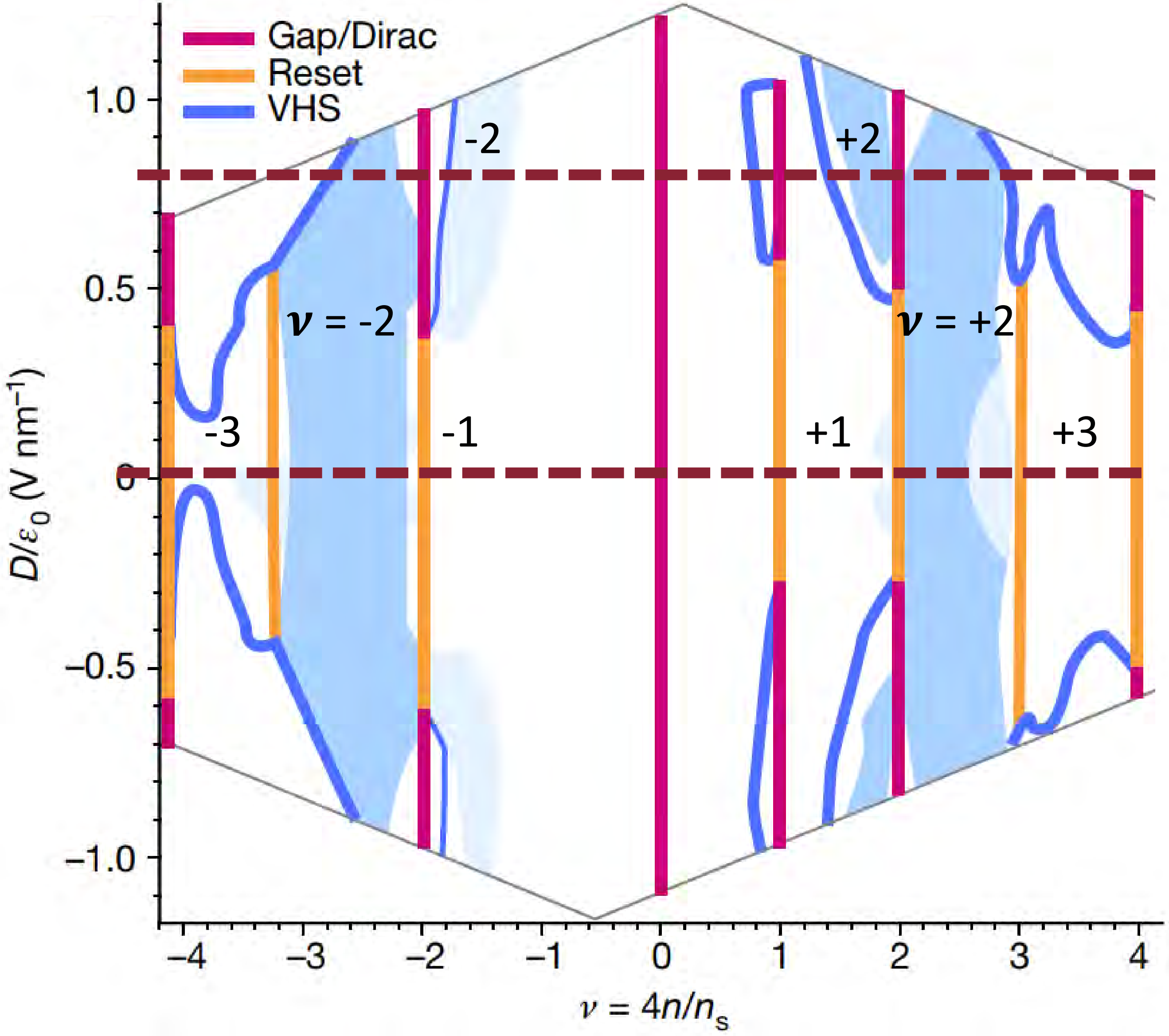


4-fold spin × valley flavor symmetry

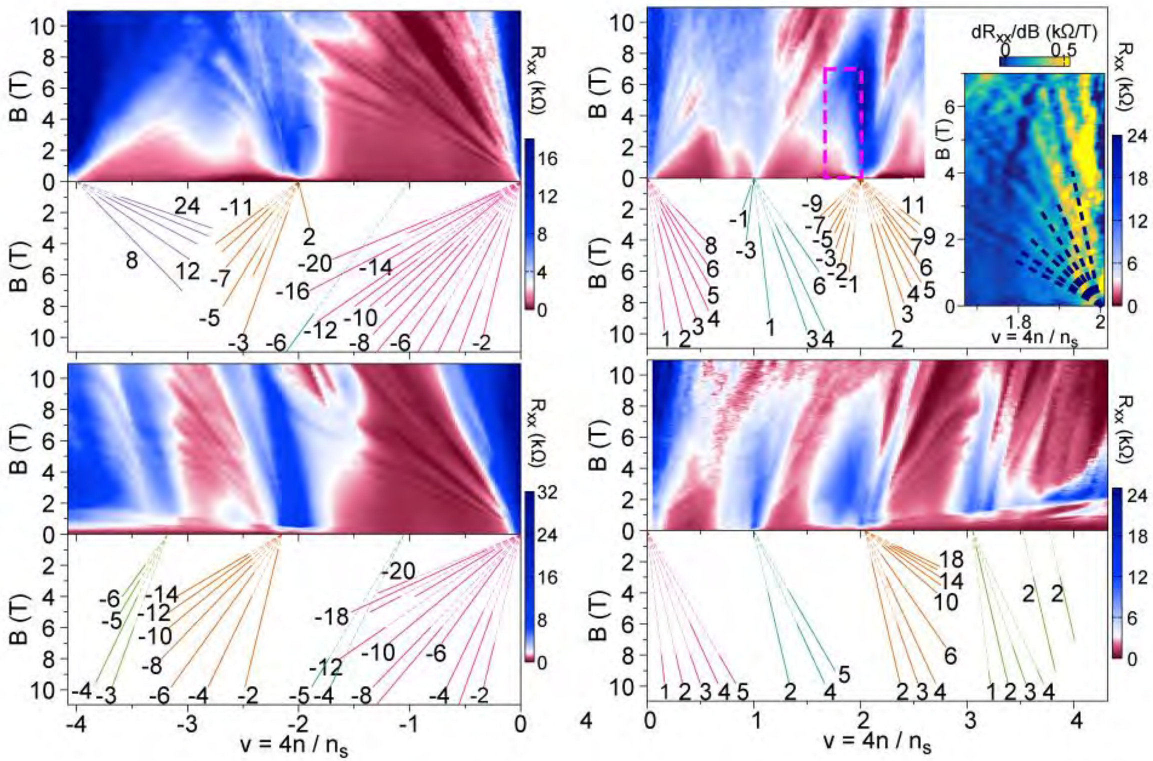
Is there **symmetry breaking?**

<u>JMP</u> et al. *Nature* **590**, 249 (2021)

SC is from the half-filling broken symmetry states



SC is only from the half-filling carriers!



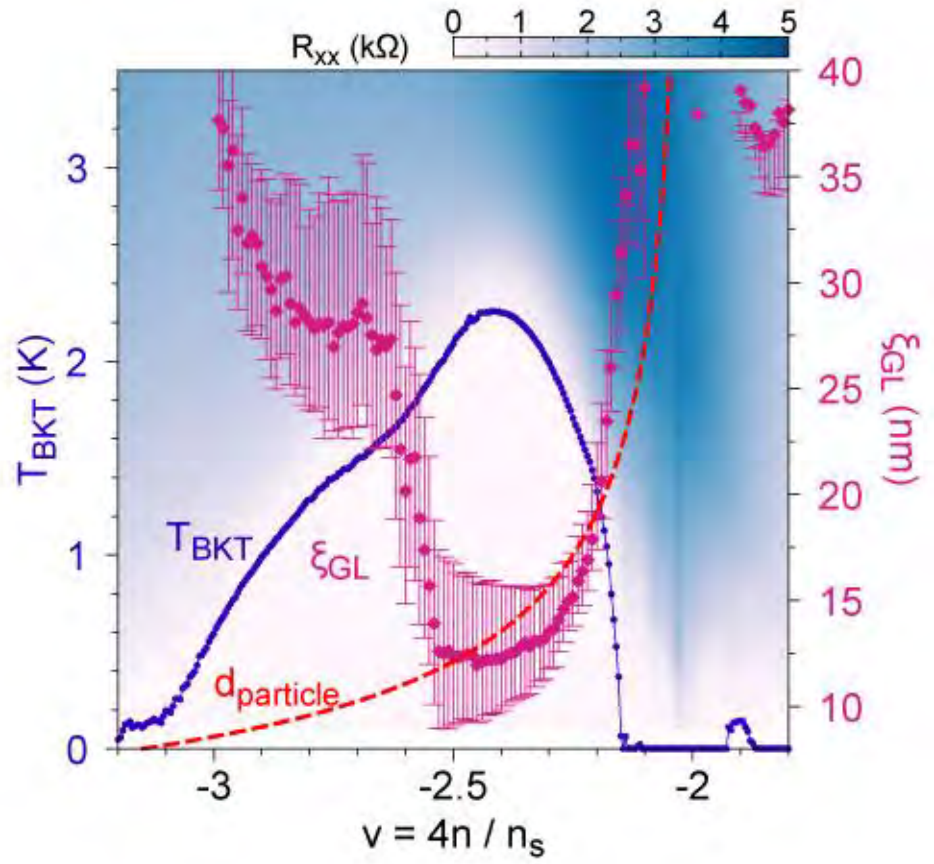
→ *Broken symmetry* at integer fillings

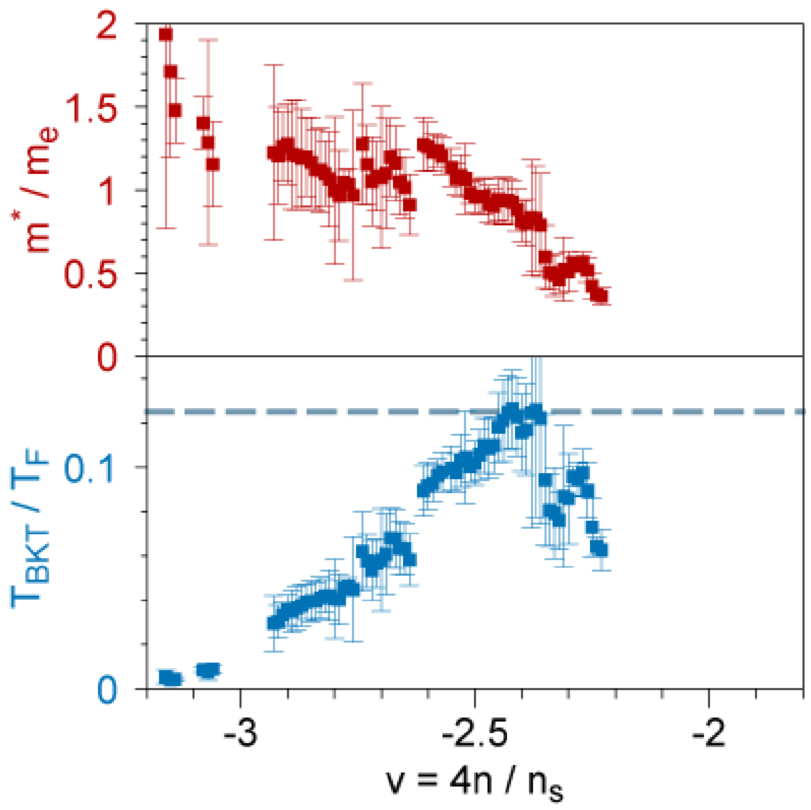
→ Electronic structures are not the same

JMP et al. *Nature* **590**, 249 (2021)

JMP et al. *Nature* **592**, 43 (2021)

Tunable strongly-coupled superconductivity





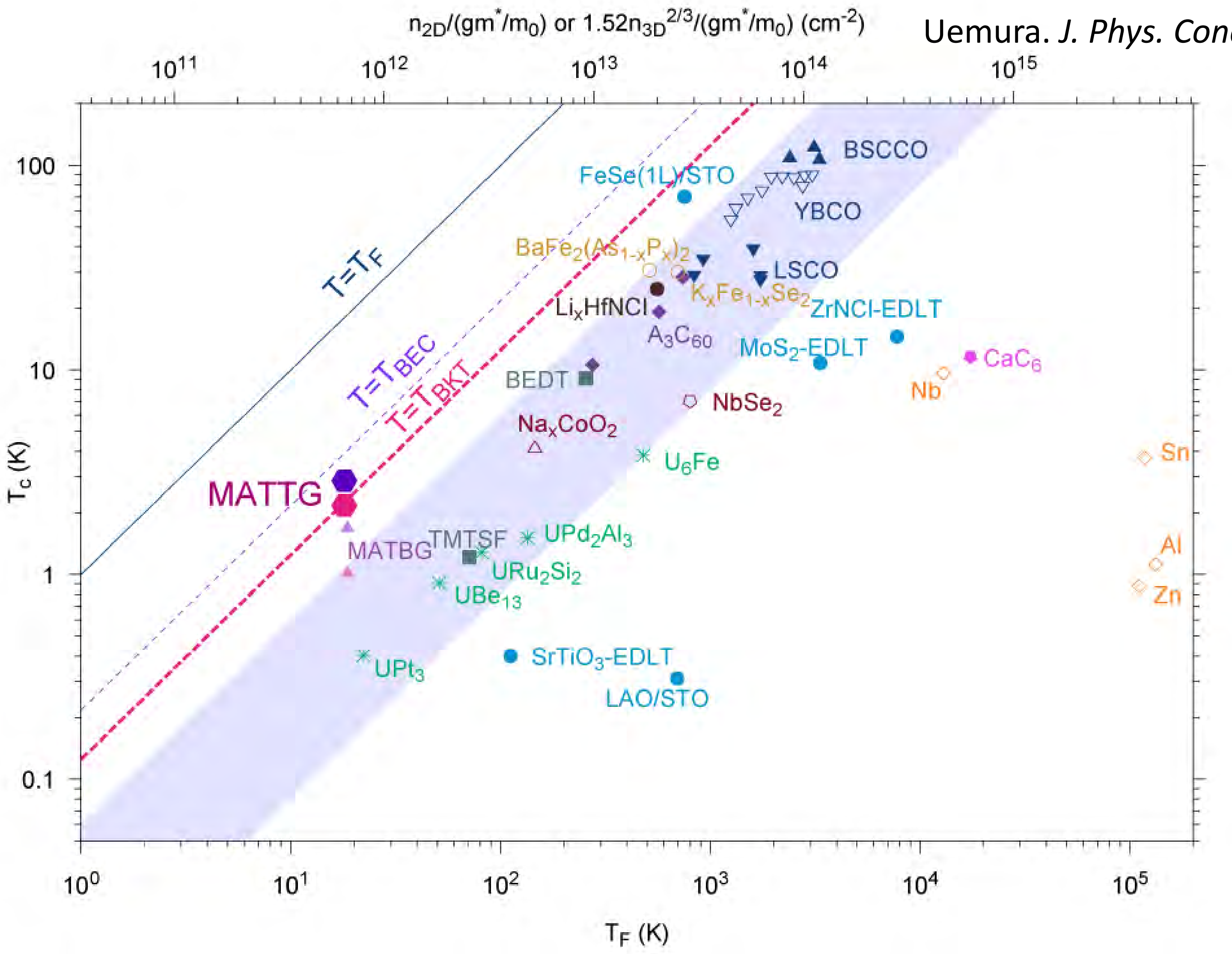
Short coherence length: Cooper pair size ≲ Interparticle distance: Strongly coupled

Large T_{BKT}/T_F ~ n_{SF}/n_e: BCS-BEC crossover regime: Strongly coupled

<u>**JMP**</u> et al. *Nature* **590**, 249 (2021)

Superconductivity is very strongly coupled!

Uemura. *J. Phys. Condens. Matter* **16**, S4515 (2004)



Our Tc is *high* for such low carrier density – Design principles for future materials

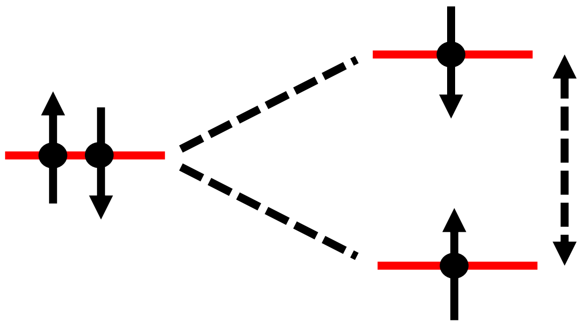
Can we probe the spin structure of SC?

SC wavefunction: (Spatial: s, p, d- wave, etc.) x (Spin: singlet, triplet, etc.)

Spin-singlet Cooper Pairs $\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

Binding energy (BCS) $\Delta_{\mathrm{BCS}} = 1.76 k_B T_C$

Zeeman effect “breaks” Cooper pairs apart



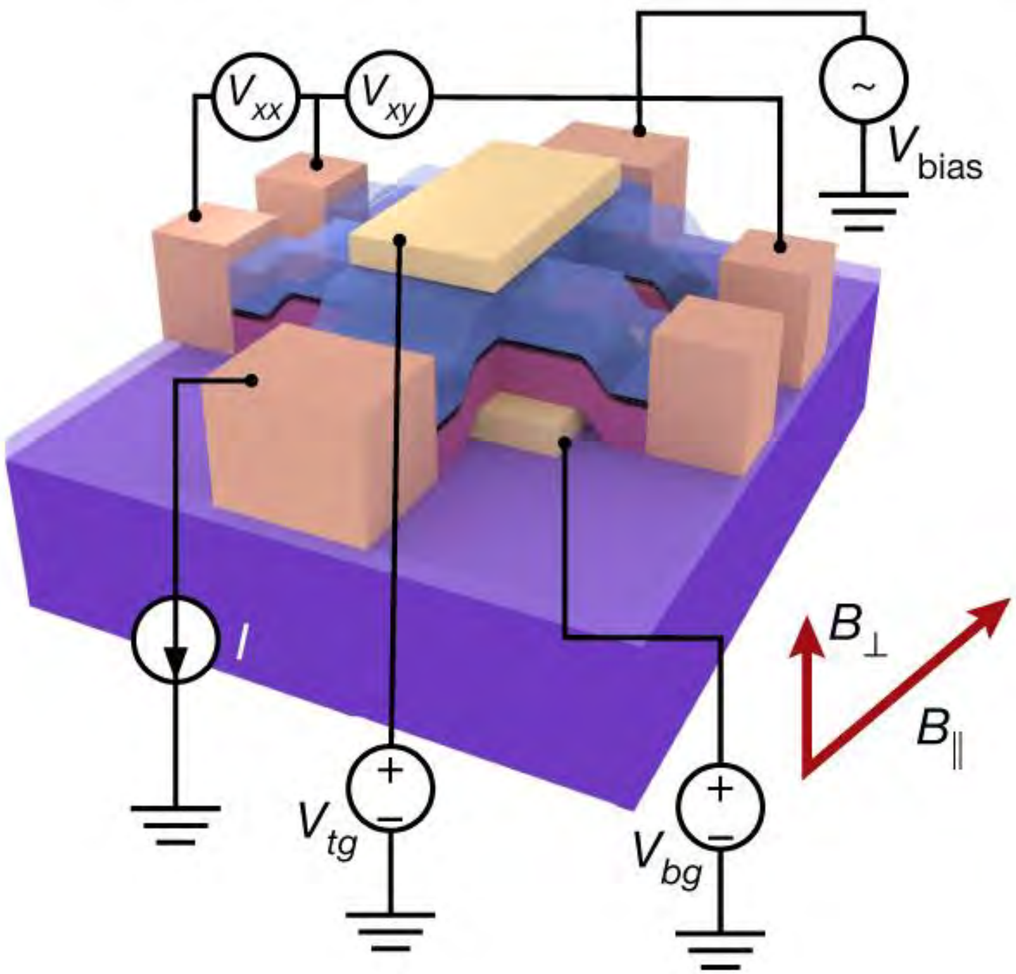
$\Delta_{\mathrm{Z}} = g\mu_B B$

Pauli limit (paramagnetic limit, Chandrasekhar-Clogston limit):

$B_P = 1.86\frac{\mathrm{T}}{\mathrm{K}} \times T_c$ (e.g. B_{P} = 1.86T for T_{C} = 1K)

for BCS spin-singlet superconductors

Can we probe the spin structure of SC?

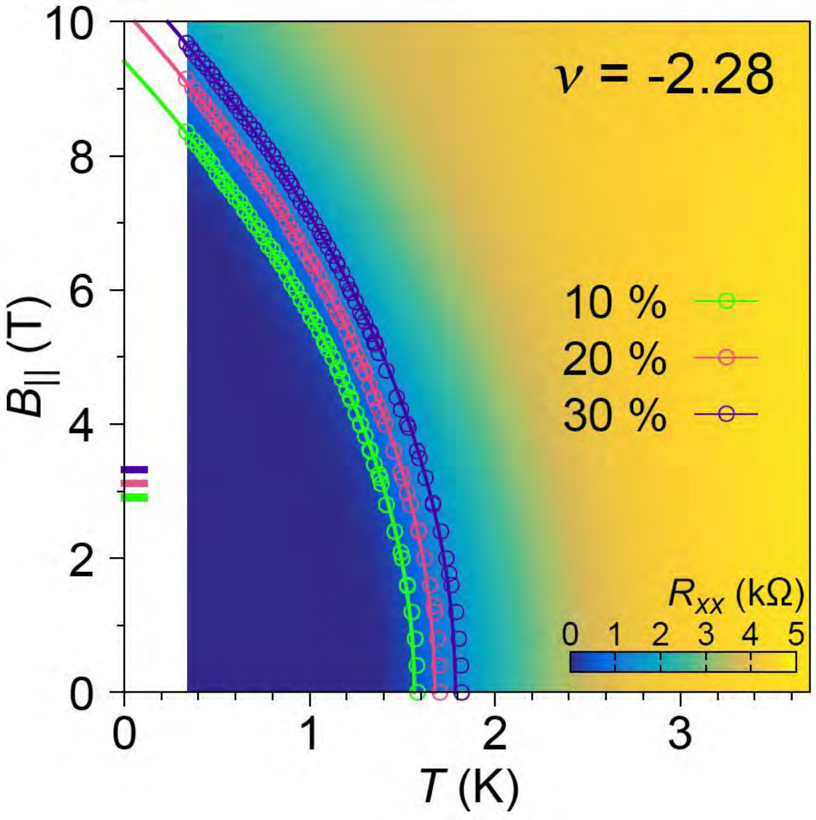


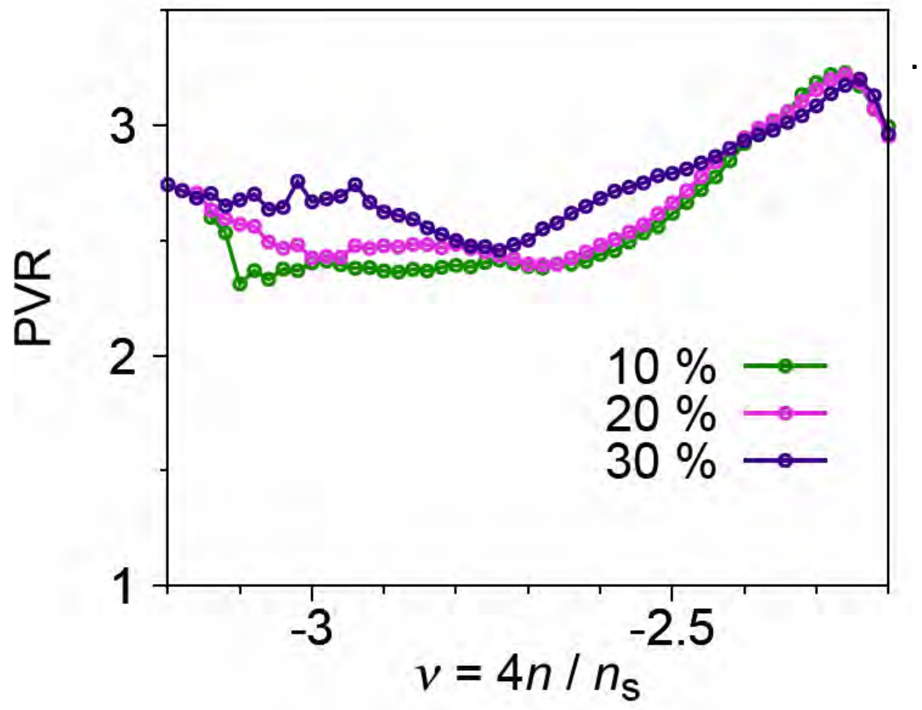
Pauli limit is violated in MATTG

Pauli limit (paramagnetic limit, Chandrasekhar-Clogston limit):

$B_P = 1.86\frac{\mathrm{T}}{\mathrm{K}} \times T_c$ (e.g. B_P = 1.86T for T_C = 1K)

for BCS spin-singlet superconductors





JMP et al. *Nature* **590**, 249 (2021)

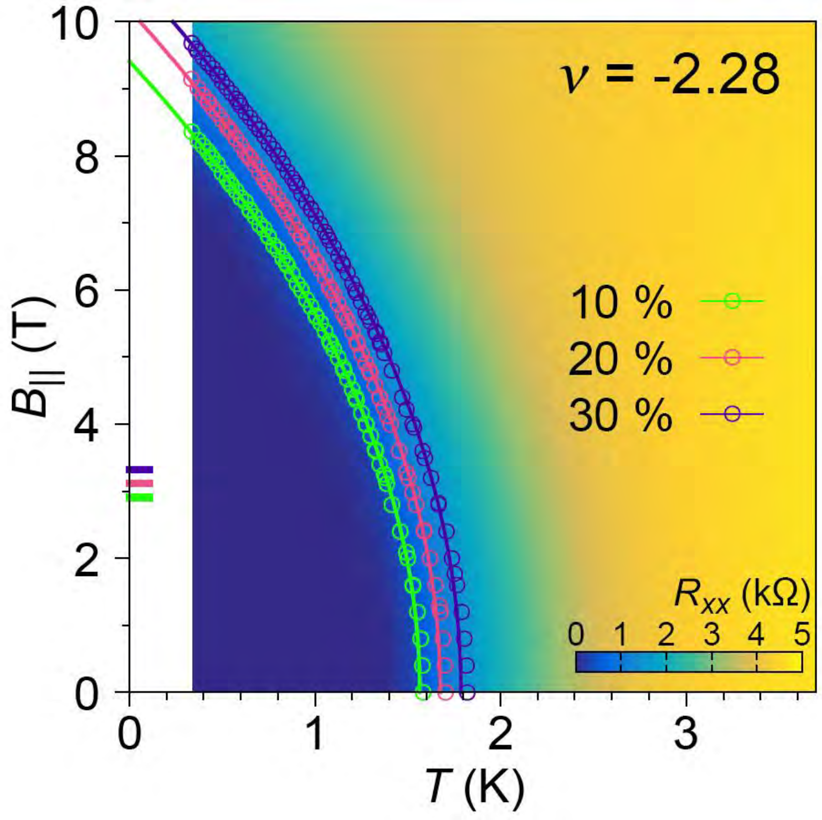
Cao*, **JMP*** et al. *Nature* **595**, 526 (2021)

Pauli limit is not violated in MATBG

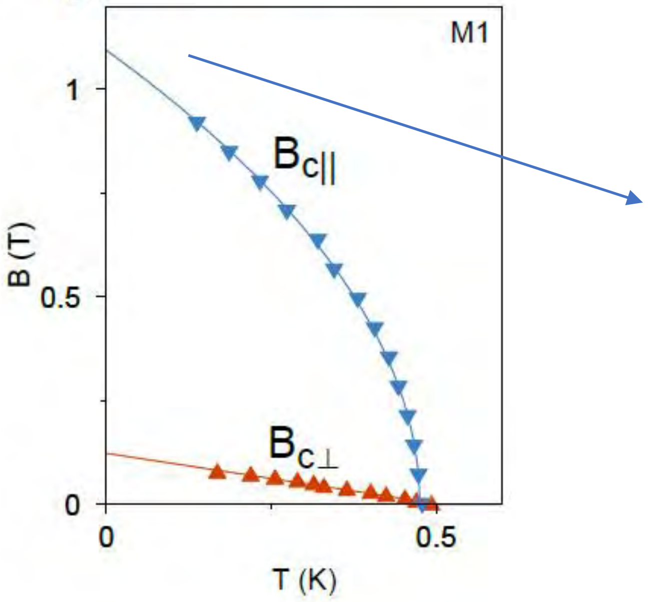
Pauli limit (paramagnetic limit, Chandrasekhar-Clogston limit):

$$B_P = 1.86 \frac{\mathrm{T}}{\mathrm{K}} \times T_c \qquad \text{(e.g. } B_\mathrm{P} = 1.86\mathrm{T} \text{ for } T_\mathrm{C} = 1\mathrm{K})$$

for BCS spin-singlet superconductors



Contrast: MATBG

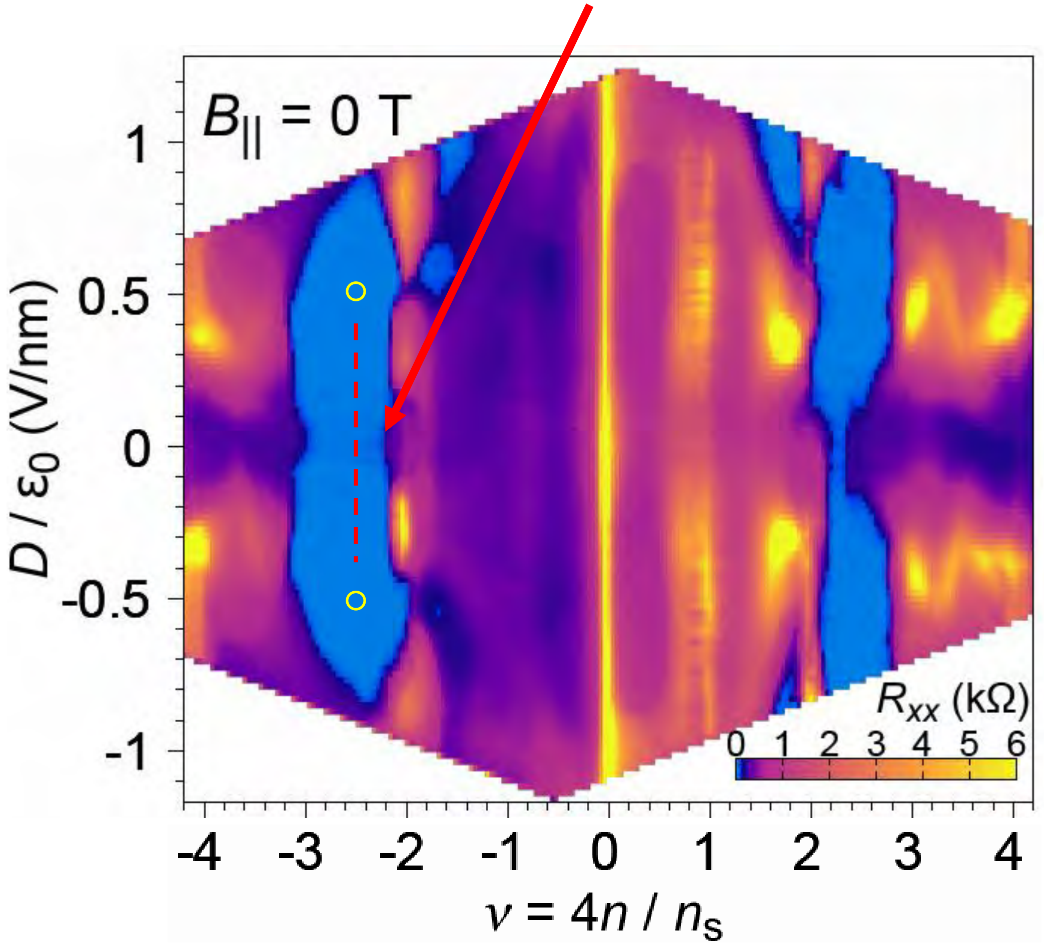


$B_{c//}$ limited around Pauli limit

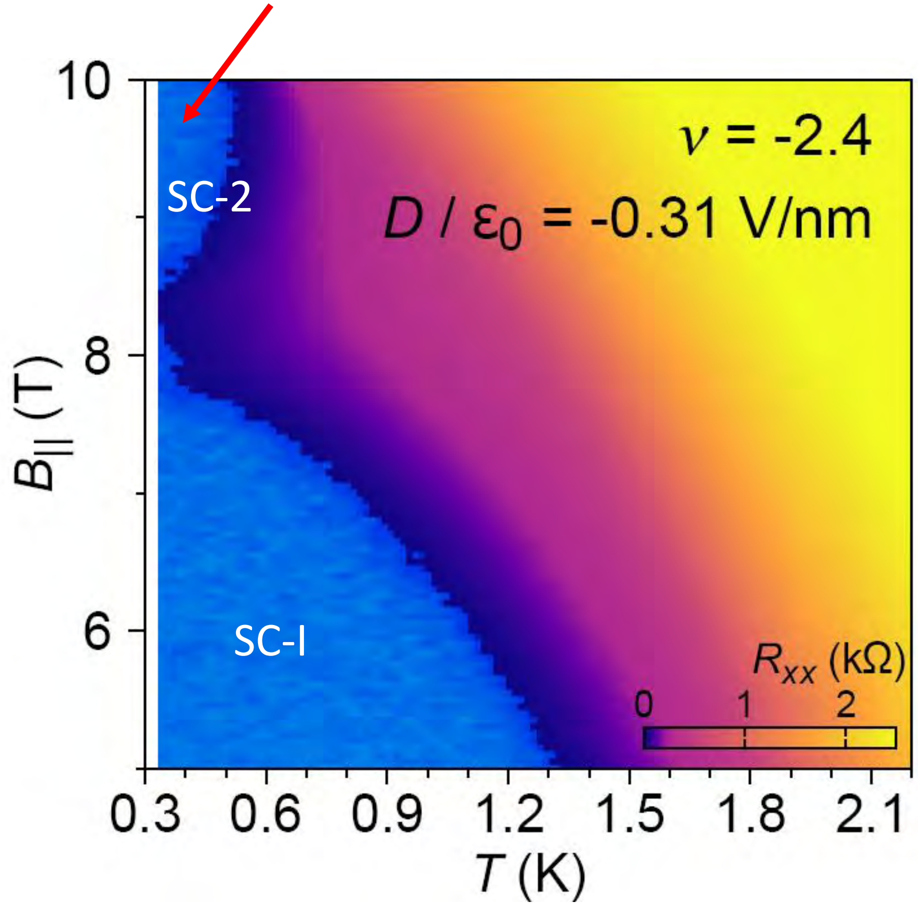
Cao*, **JMP*** et al. *Nature* **595**, 526 (2021)

Reentrant superconductivity in MATTG

At a different displacement field…



Reentrant superconductivity at high B

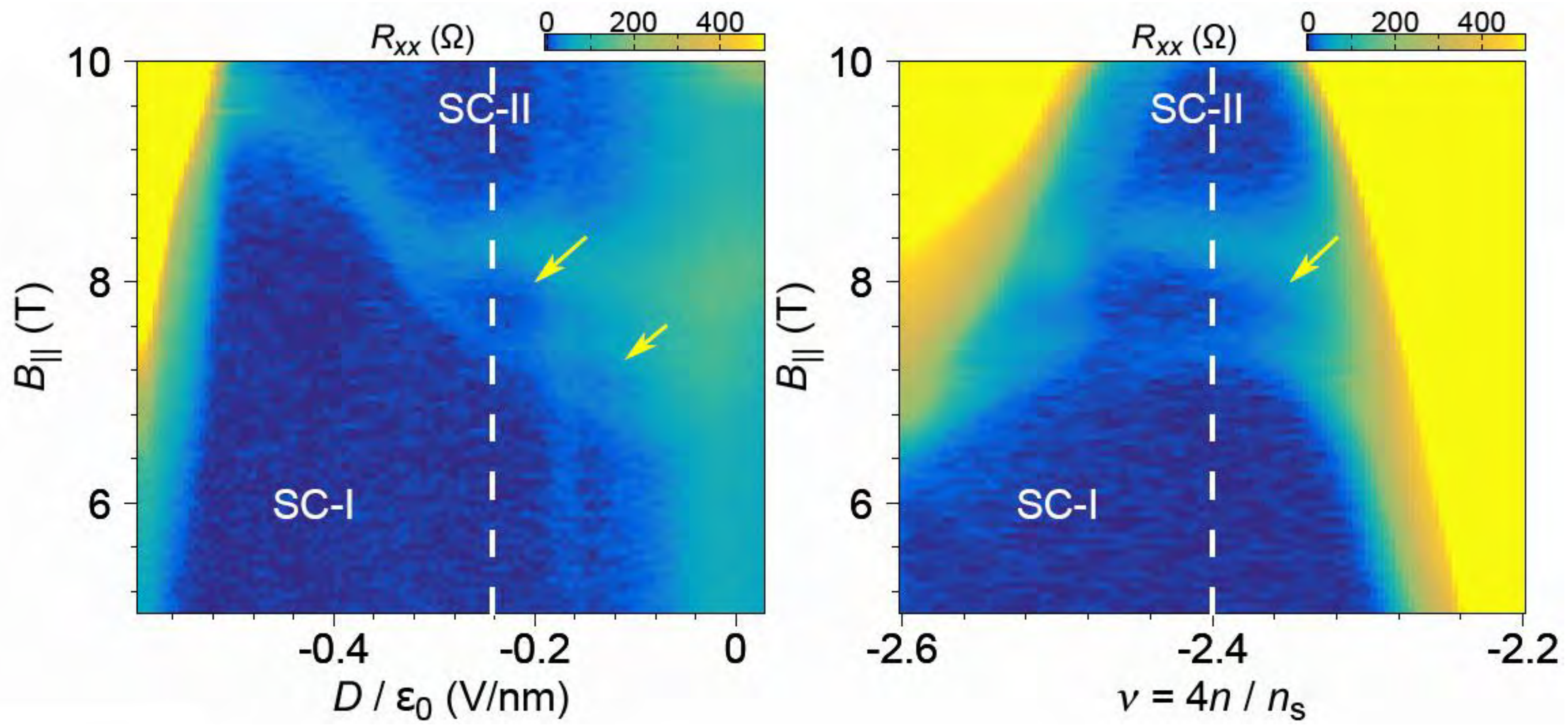


Cao*, **<u>JMP*</u>** et al. *Nature* **595**, 526 (2021)

Tunable reentrant superconductivity

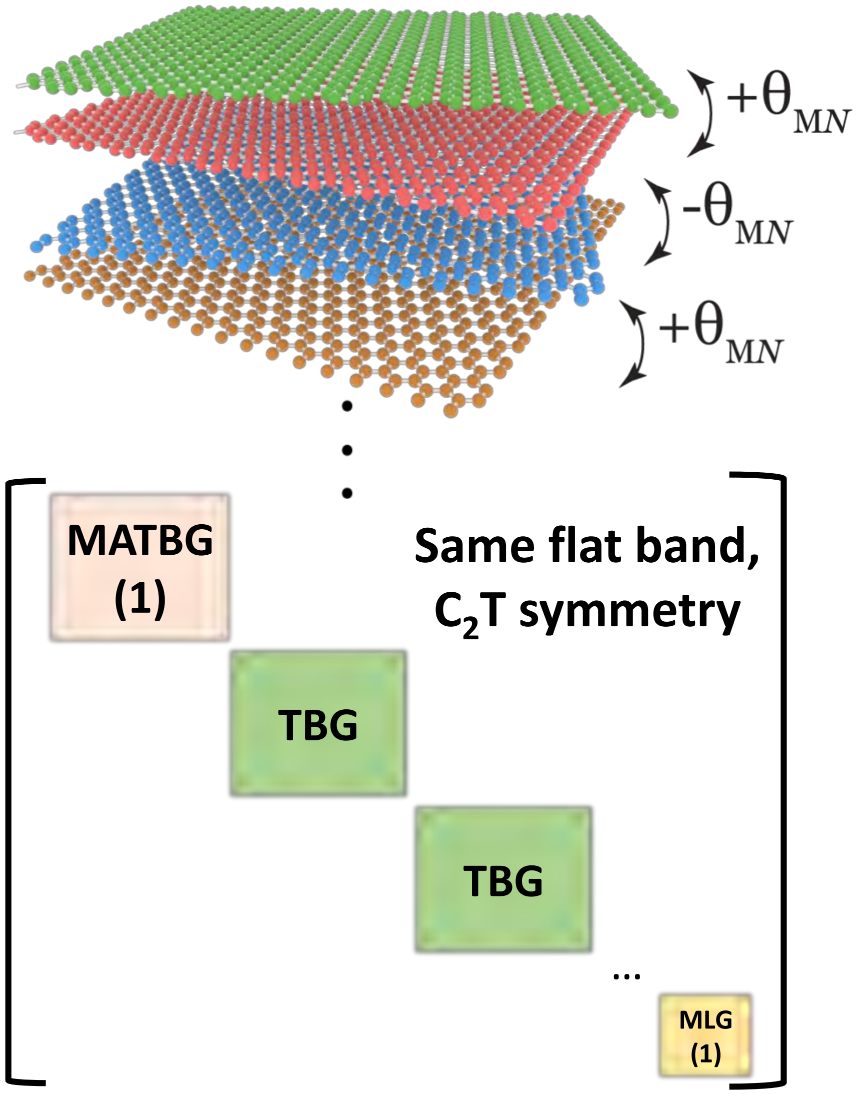
Displacement field

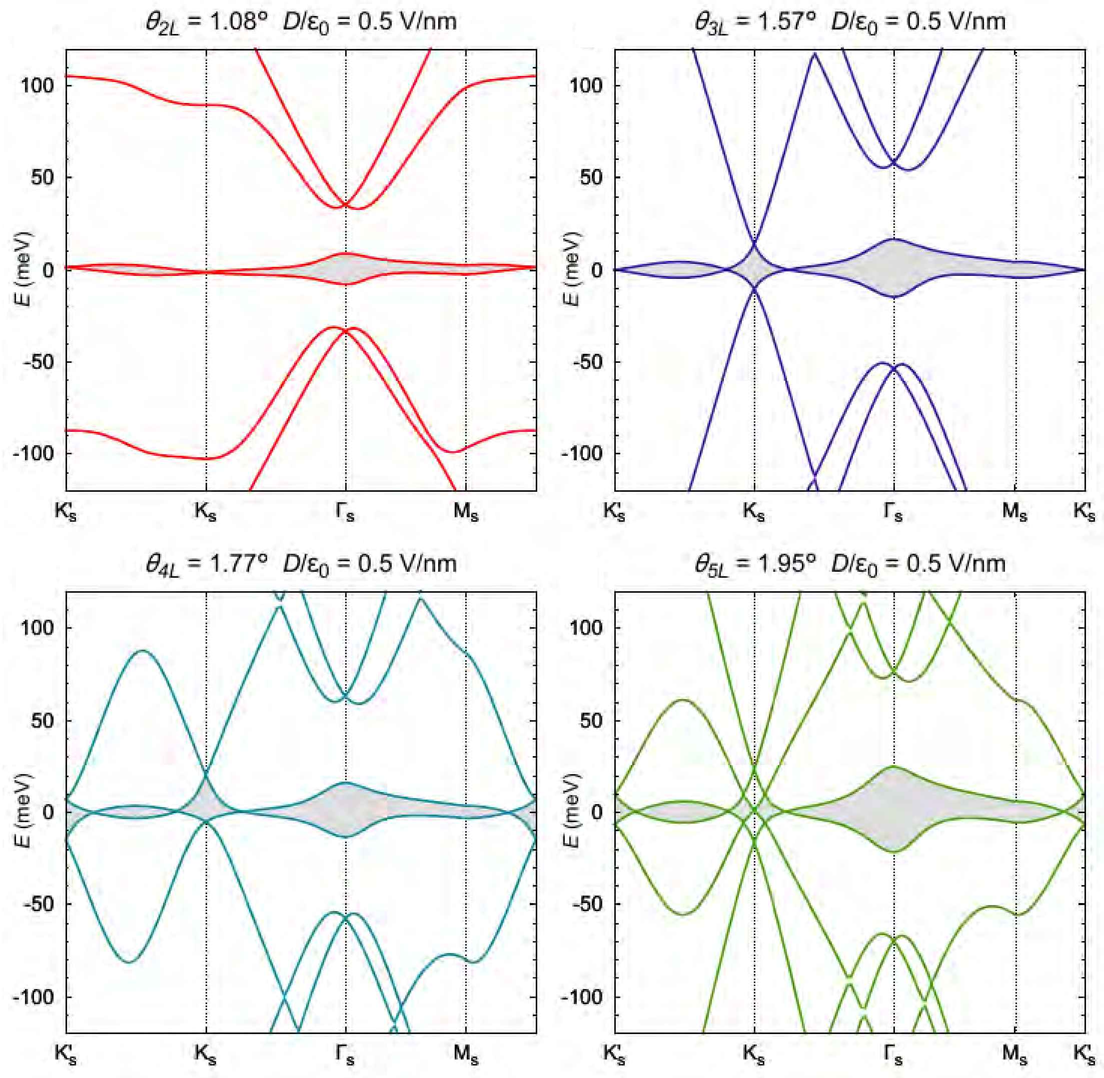
Doping



- 2-dimensional materials for strongly correlated physics
  - Magic-angle twisted bilayer graphene
- Magic-angle twisted trilayer graphene
- The magic family
- Outlook

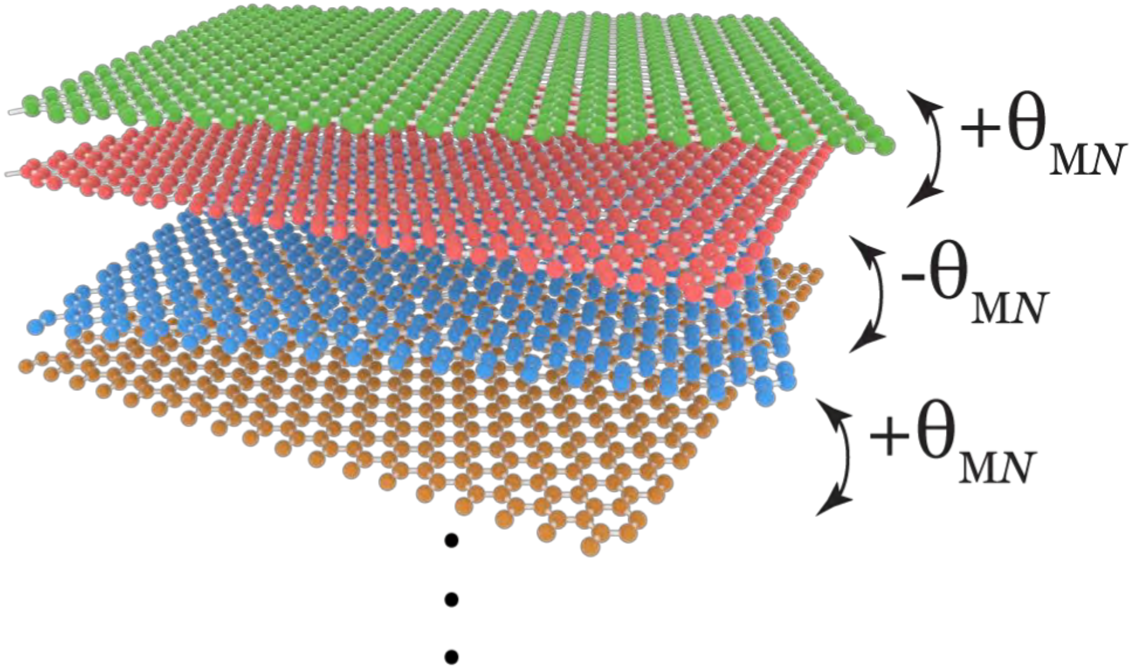
The magic extends!

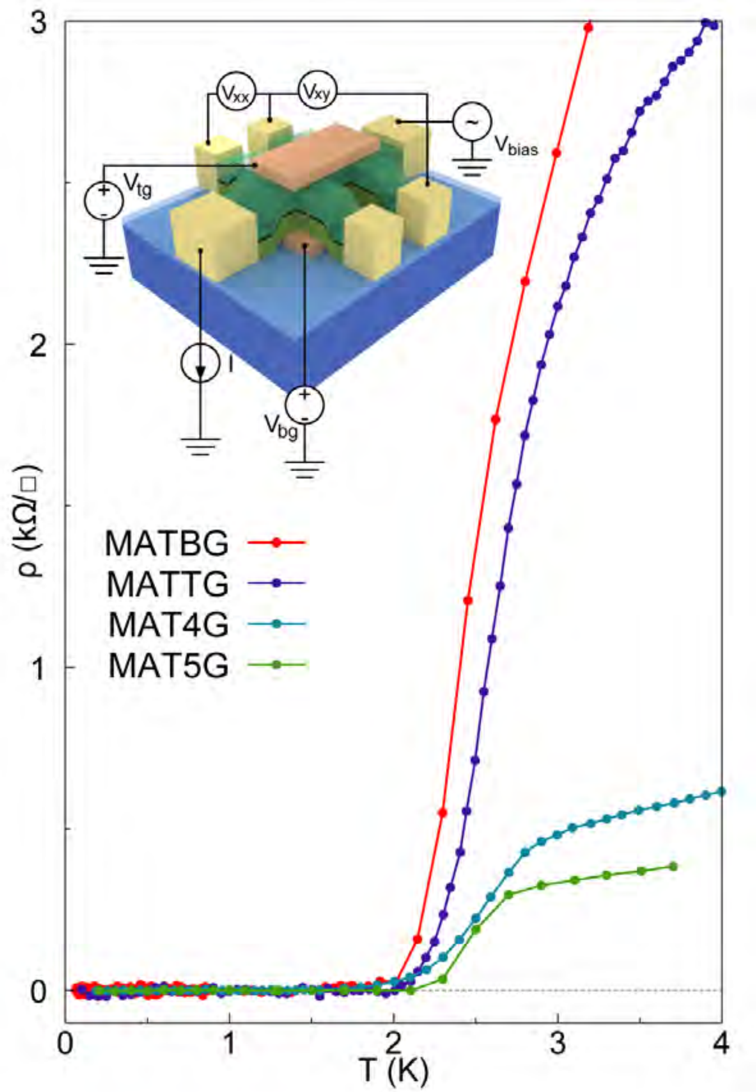




Khalaf et al. *Phys. Rev. B* **100**, 085109 (2019)

The magic family of robust superconductors



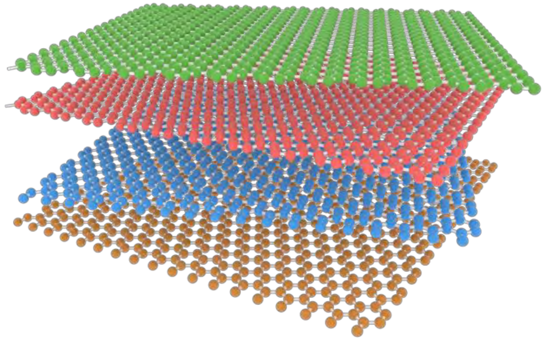


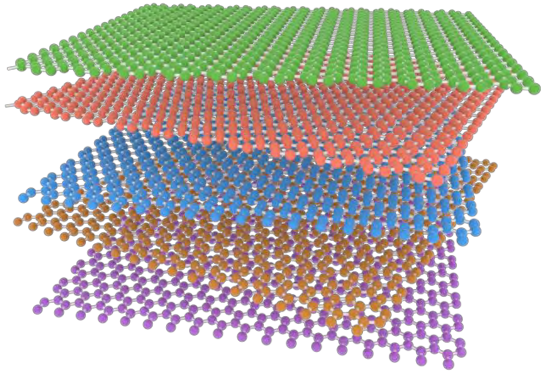
Family of strongly-coupled superconductors!

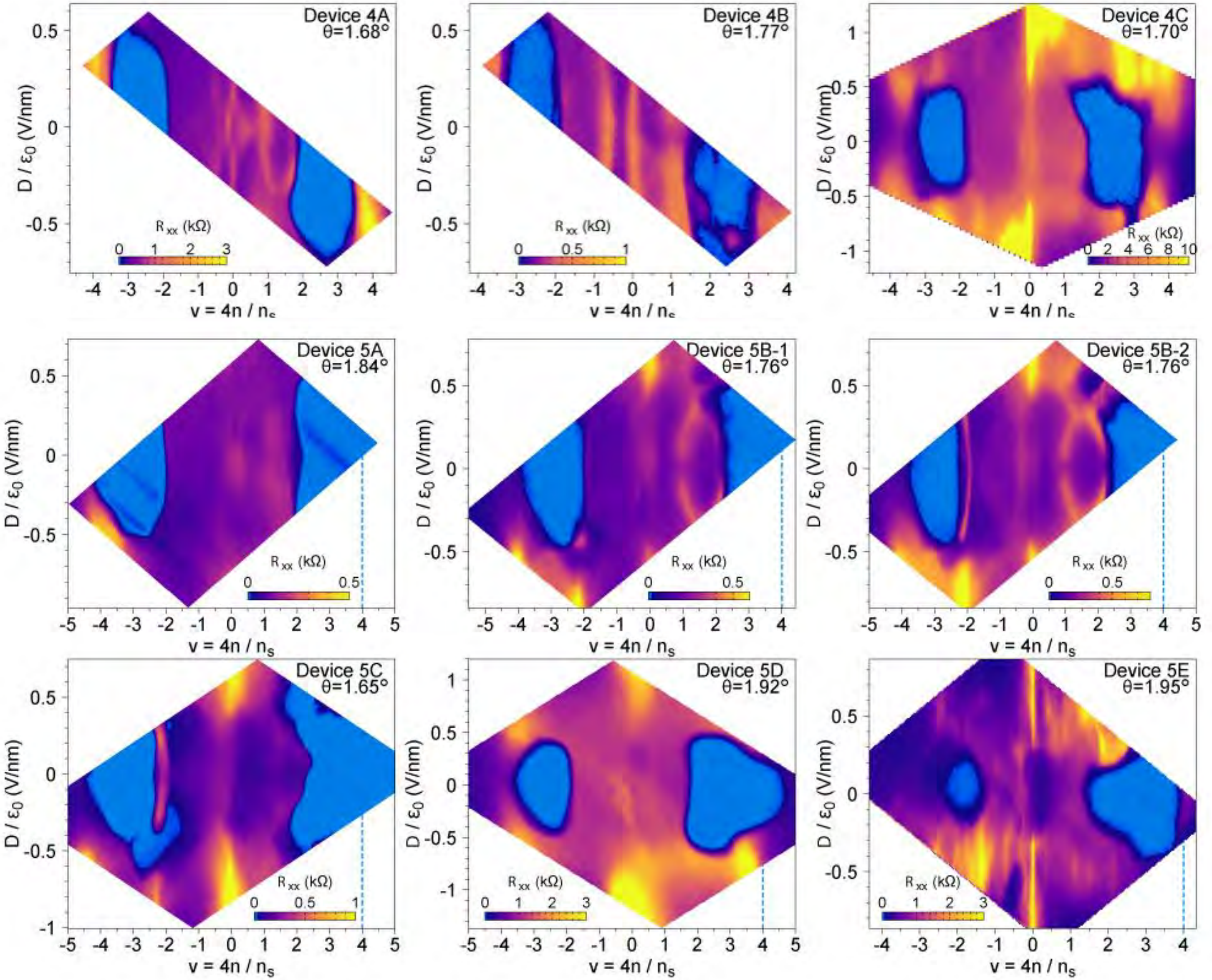
See also: Nadj-Perge Group. *Science* **377**, 1538 (2022)

<u>**JMP**</u> et al. *Nature Materials* **21**, 877 (2022)

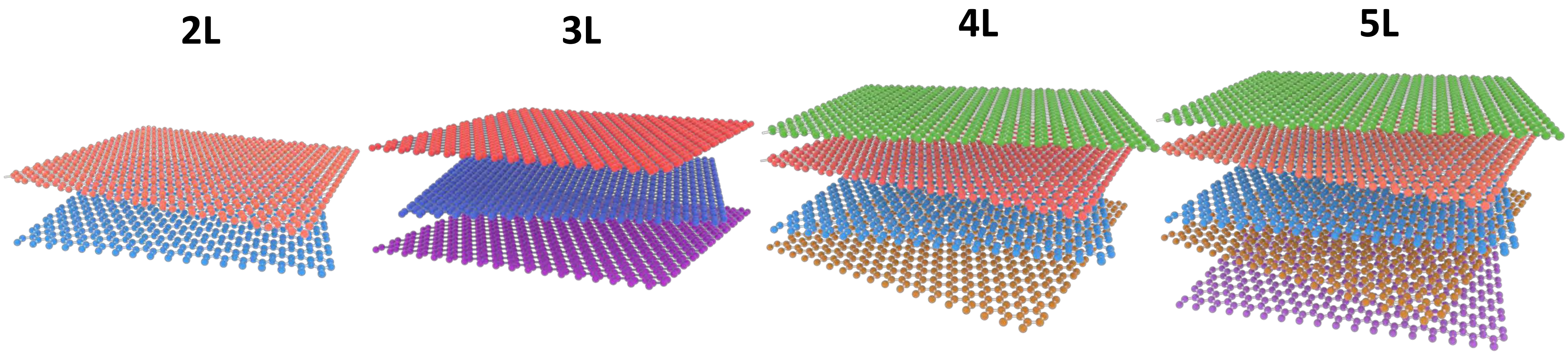
~100% magic rate





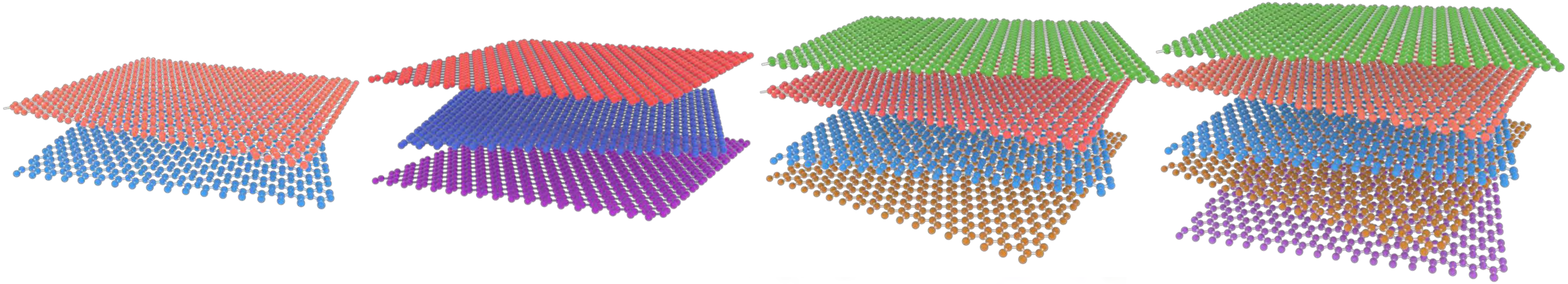


The magic family

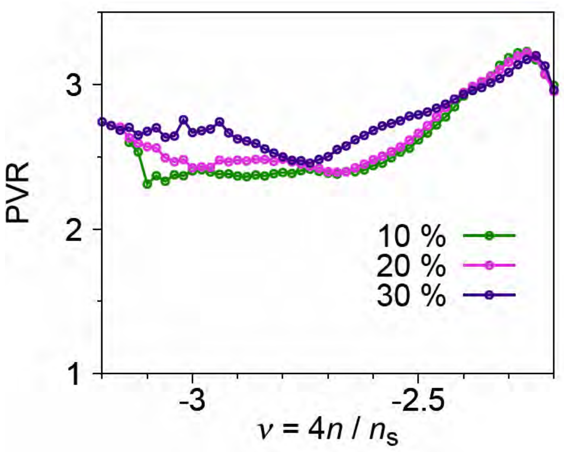


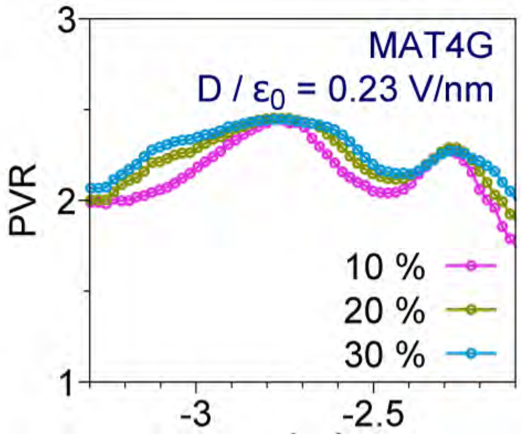
Pauli limit violation

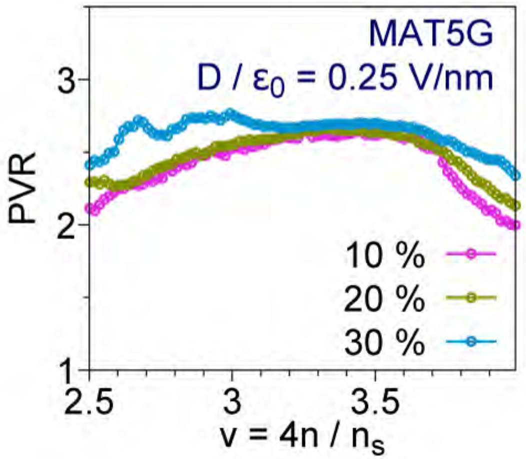
2L | 3L | 4L | 5L



Not violating the Pauli limit







Only 3-5L consistently violate the Pauli limit

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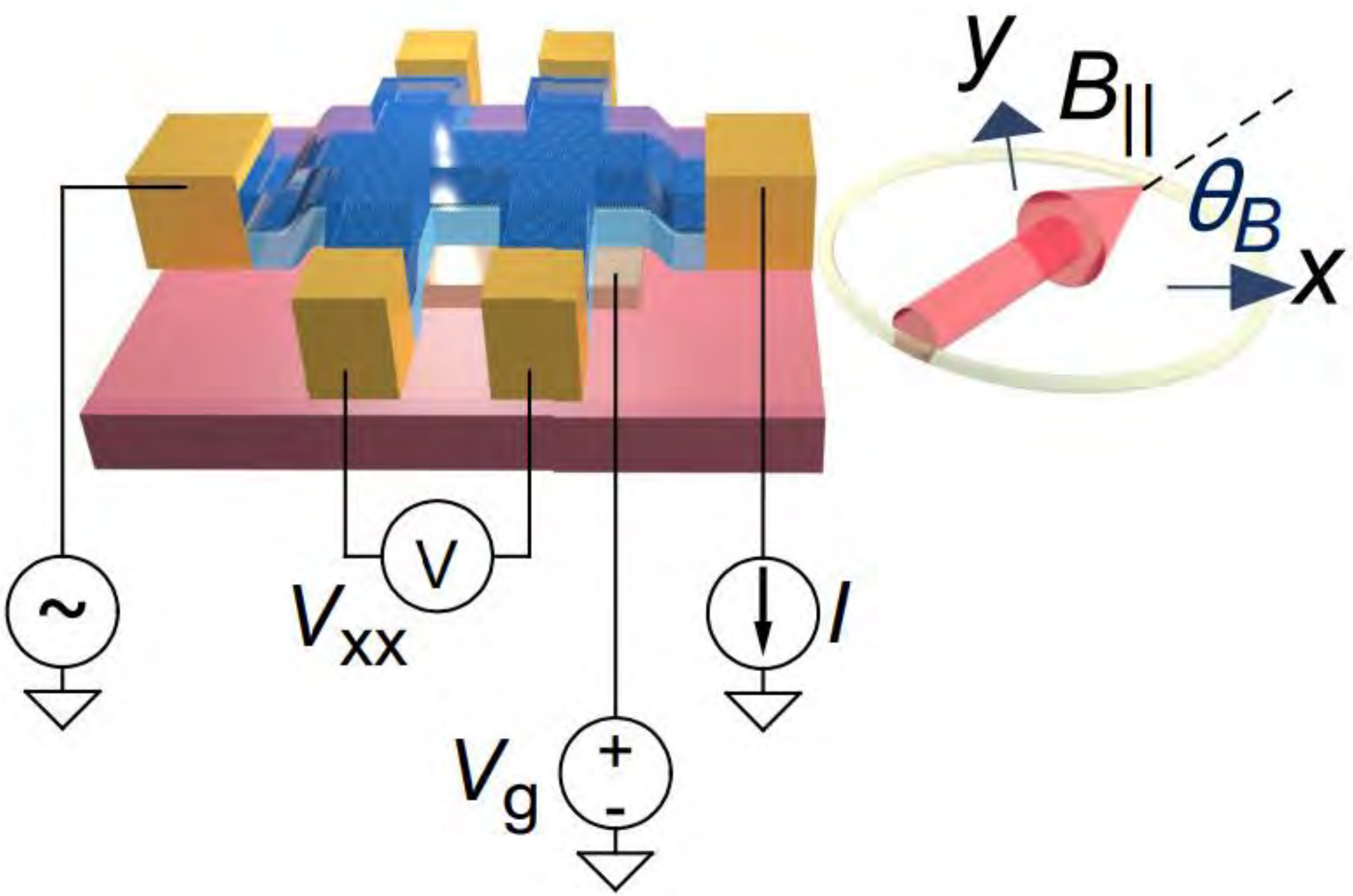
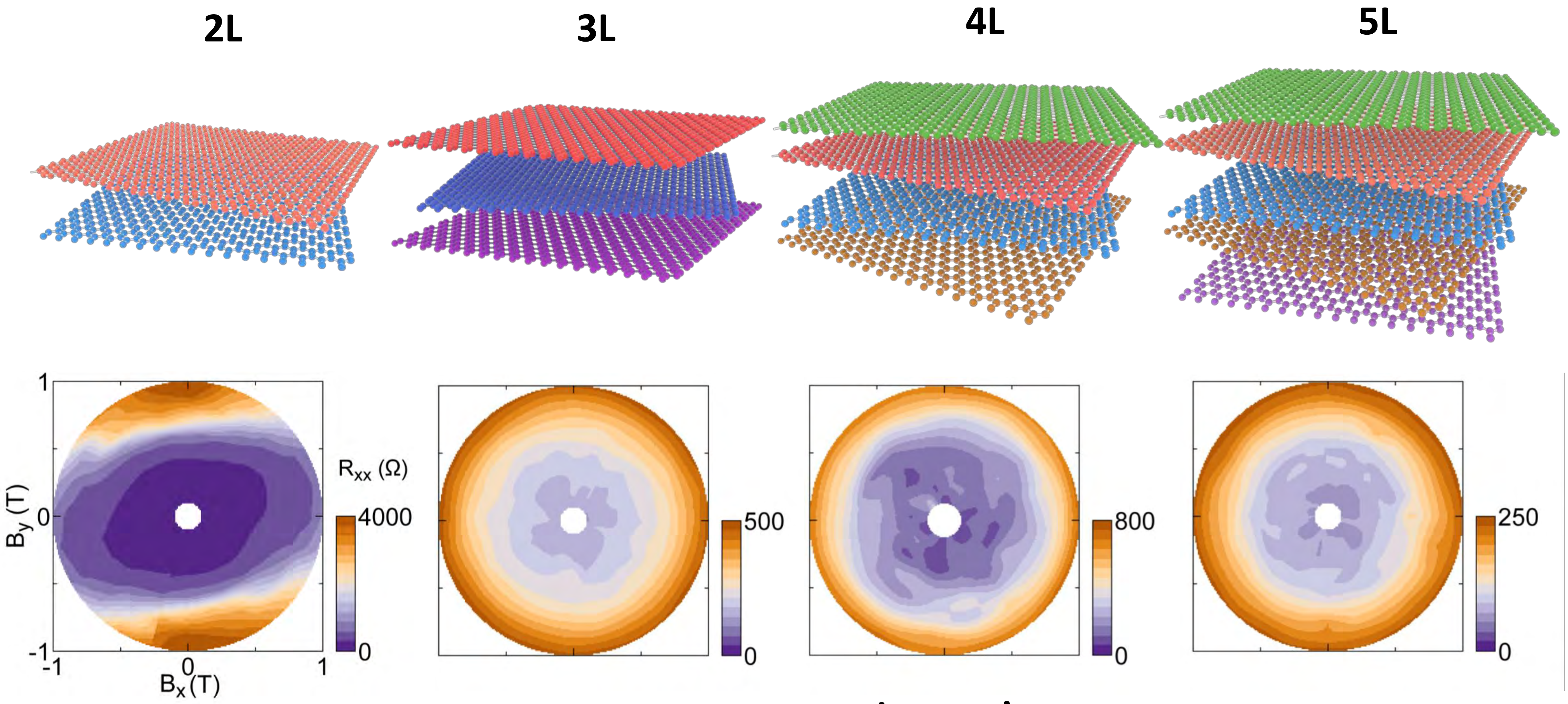
Angle-dependent magnetic field response



Spontaneous breaking of rotational symmetry



Anisotropic

Isotropic

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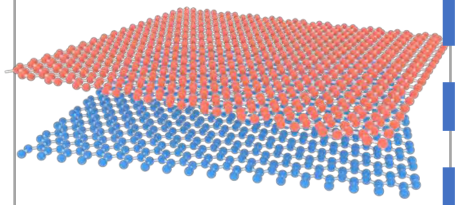
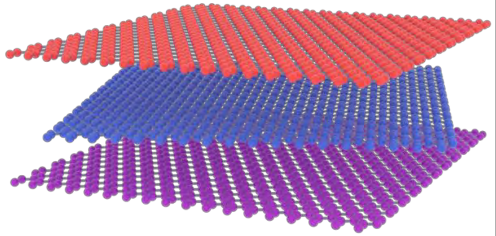
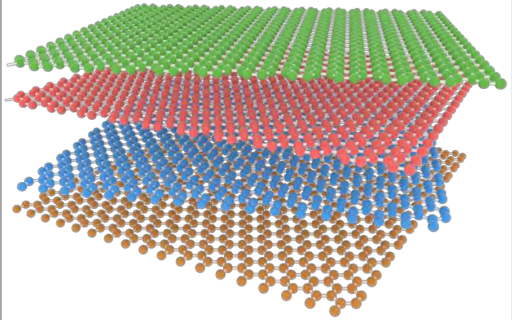
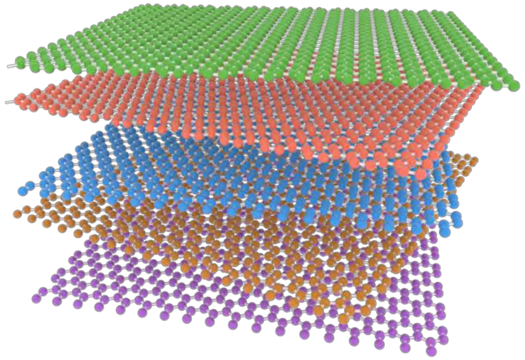
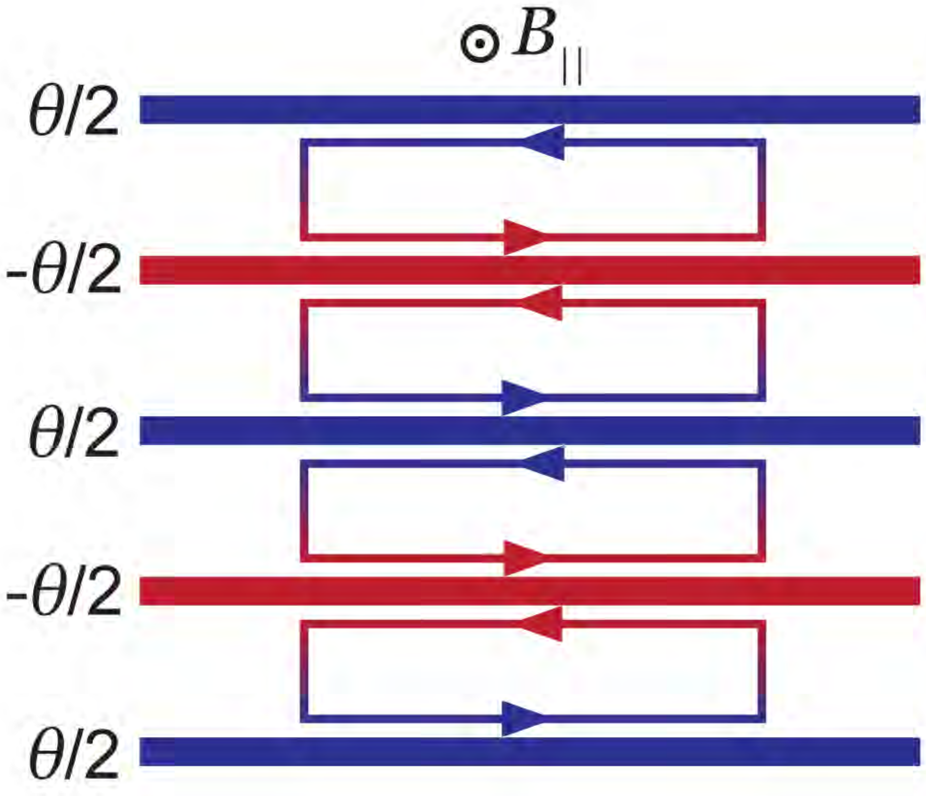
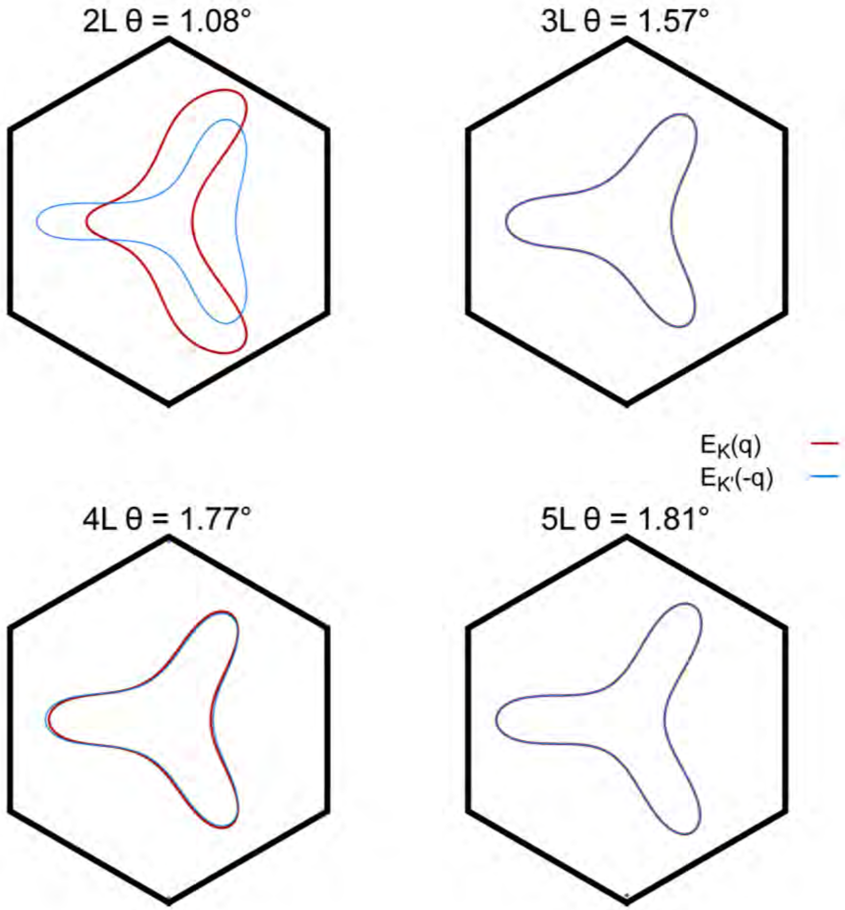
The magic family

	2L	3L	4L	5L
				
Correlated Insulator	✓	✓	✓	✓
Superconductivity	✓	✓	✓	✓
Pauli limit violation		✓	✓	✓
Nematicity	✓			

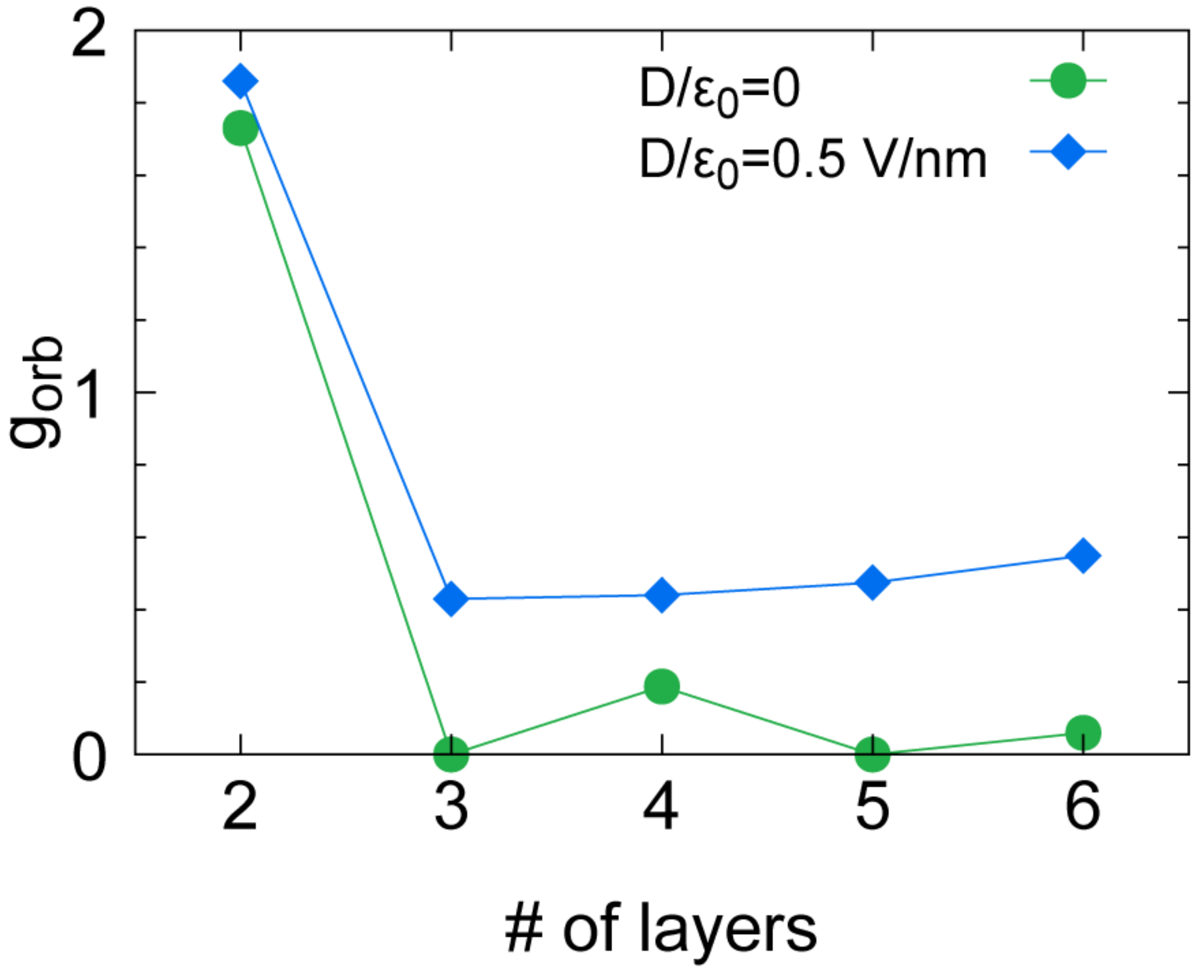
In-plane orbital effect





(1) Fermi surface deformation → SC killed
(2) Anisotropy → Nematicity

In-plane orbital effect



In-plane orbital effect explains the difference among the magic family members

Conclusion & Outlook

☑ Can we design a tunable, strongly coupled superconductor?

Yes, much beyond! MATTG as a new platform for correlated physics

- Exceptional tunability for a new dimension in phase space
- Ultra-strongly coupled superconductivity
- Large Pauli limit violation and reentrant superconductivity

☑ Can we find important ingredients or recipes?

Yes, the *Magic family* of robust moiré superconductors is established

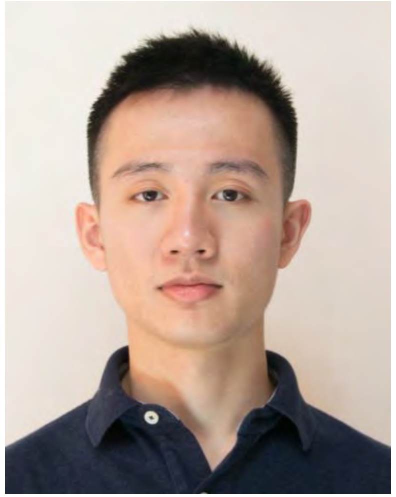
- All share the same type of flat band
- Importance of C_2T symmetry

Future directions

- SC order parameter of the magic family members, microscopic structure?
- Can we increase the Tc? Or design ideas for high Tc?
- Coupling with topological phases

Acknowledgement

Pablo Jarillo-Herrero



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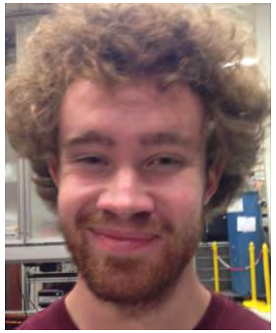

Andrew Pierce

hBN crystals:
Kenji Watanabe
Takashi Taniguchi

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